CLAS12 Exclusive $\omega(782)$ Meson **Feasibility** Analysis

Zhaozhong Shi

03/12/2026

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Physics Motivation

15	Inclusive Double-Charged Pion (omega) (ep → e'p'π⁺π⁻(π⁰)) Channel	Resonance Region, All RG-A Data	TBD	Zhaozhong Shi, Philip Cole	Lamar University	2025	2028	TBD

Organization

Nuclear Physics Group

Senior PI   Junior CoPI

Milestone

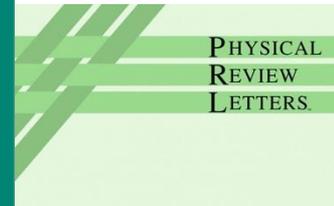**CLAS12 Proposal**

CLAS12 RG-A - Analysis Note Overview and Procedures Phase I
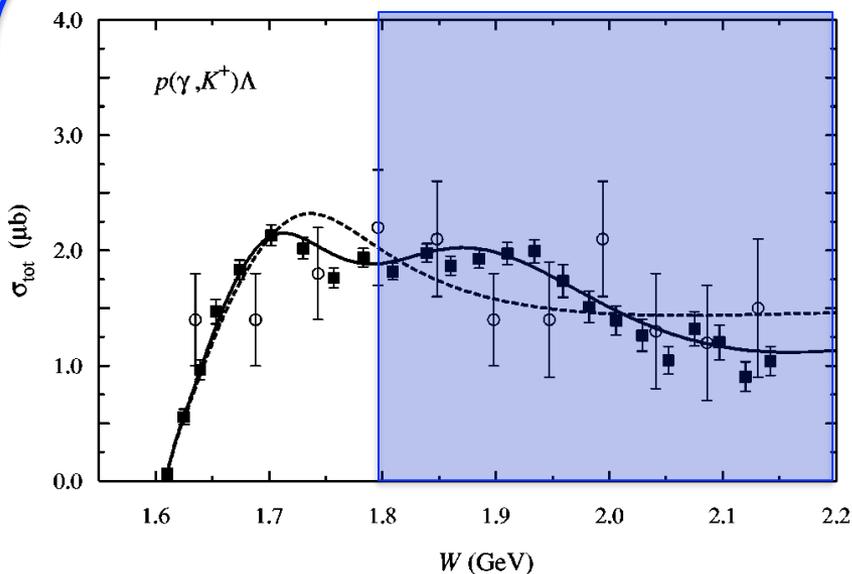Towards SIDIS CLAS12 First Publications
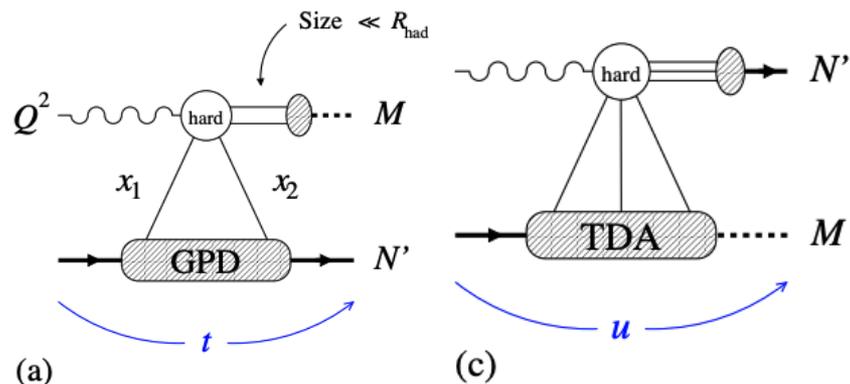

Deliverables

ω Meson Physics Program at Lamar

N^* Physics

- Physics: Baryon spectroscopy $N^* \rightarrow \omega N$ for $1.8 < W < 2.2$ GeV
- Observable: cross section and partial wave amplitude analysis, branching ratios
- Target journal: PRC or PRL
- Funding: NSF grant from 2025 – 2027

GPD Physics

- ω vector meson electroproduction: $\gamma^* N \rightarrow \omega N'$ for $W > 3.0$ GeV
- Observable: A_{LU} and lead to GPD and TDA results at high Q^2 (high $|t|$ and $|u|$) with the help of CVT
- Target journal: PRC or PRL
- Funding: future NSF grant from 2027 – 2030

- This ω meson physics proposal is correctly endorsed by Hall B leader Stepan Stepanyan
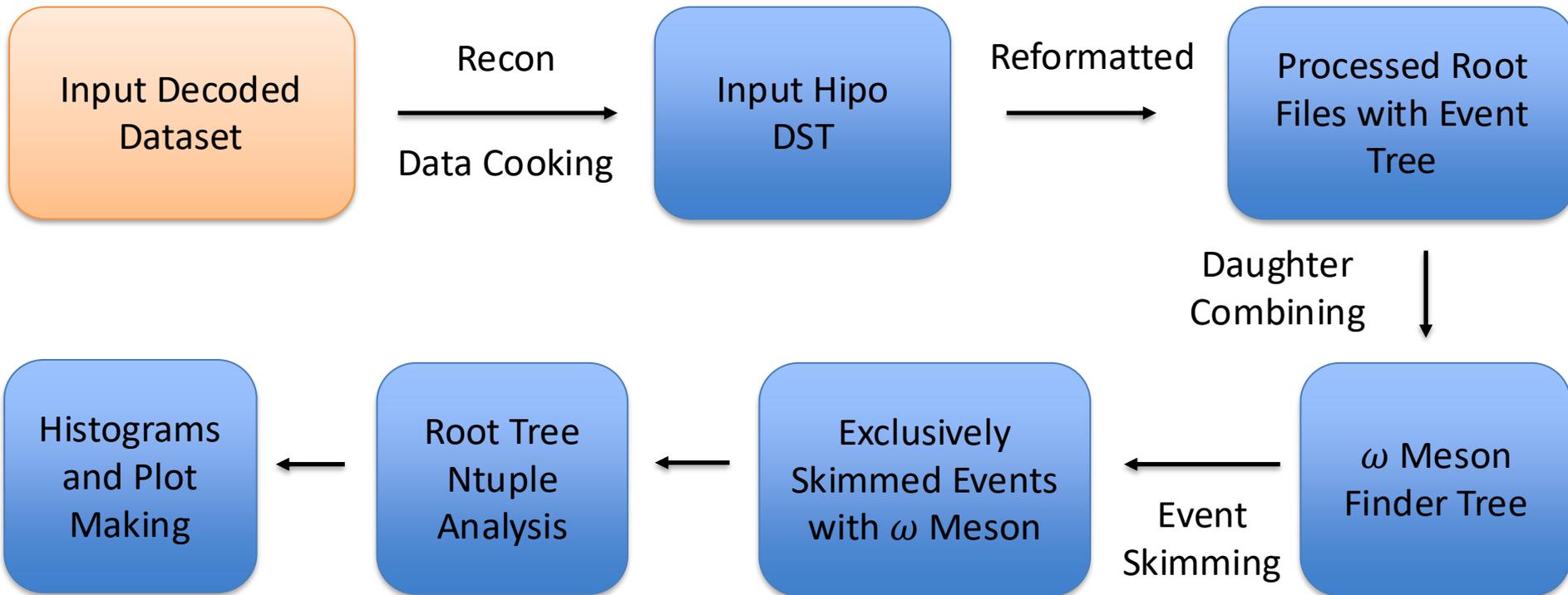
Exclusive ω Meson Decay Channels

$$ep \rightarrow e'p'\omega \rightarrow \pi^+\pi^-\pi^0 \rightarrow \pi^+\pi^-\gamma\gamma$$

$$ep \rightarrow e'p'\omega \rightarrow \gamma\pi^0 \rightarrow \gamma\gamma\gamma$$
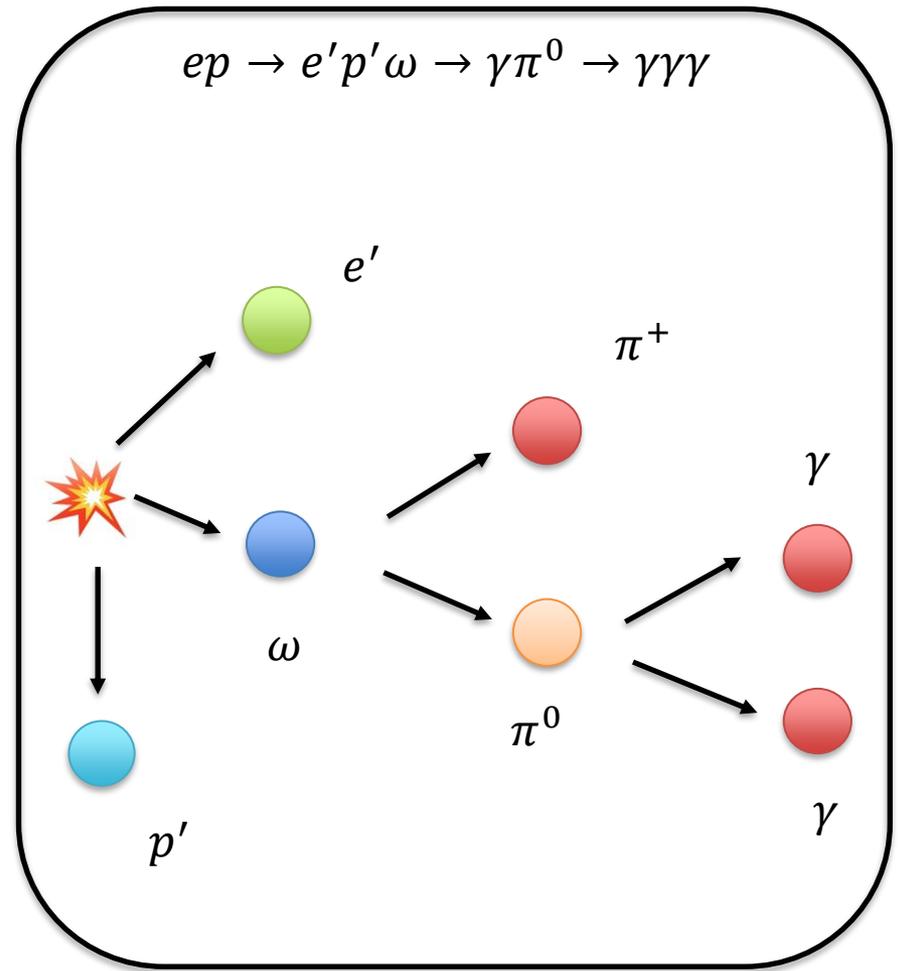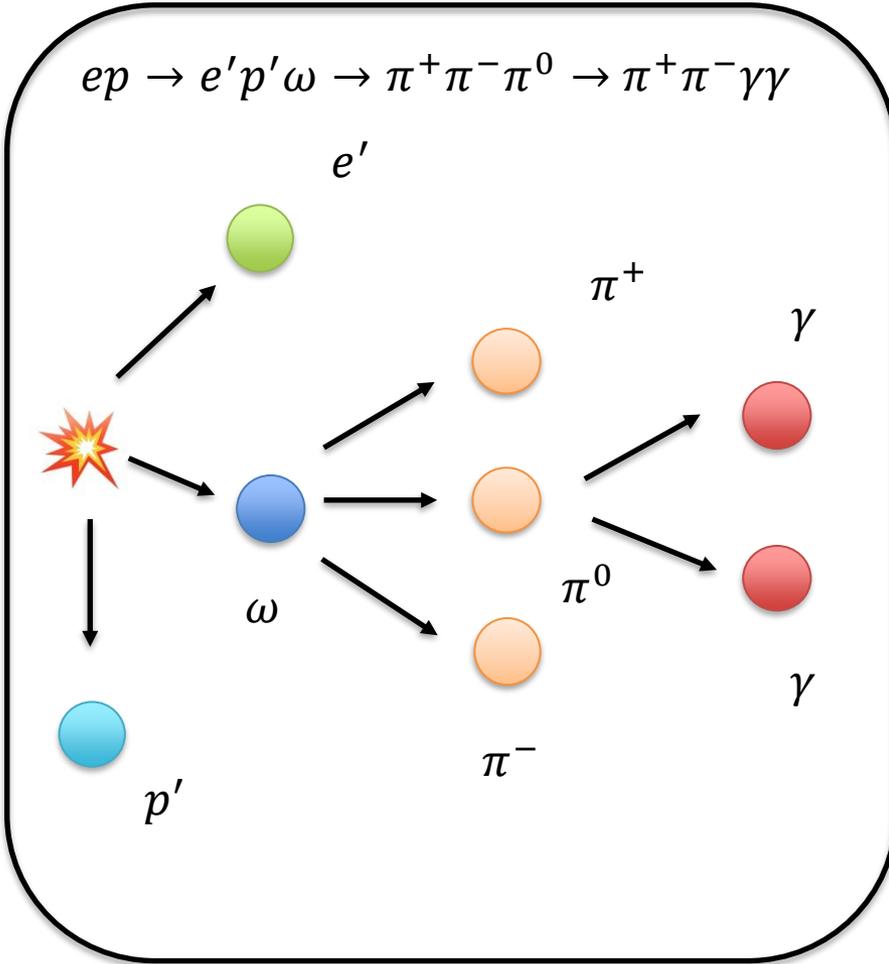
- We observed the signal for two channels, which makes this talk possible
- The focus is on the ω resonance and raw yield statistics: that is feasibility studies as the first the status report for my analysis

Sample Processing

Analysis Pipeline Design

Input Decoded Dataset → **Recon / Data Cooking** → Input Hipo DST → **Reformatted** → Processed Root Files with Event Tree

Processed Root Files with Event Tree → **Daughter Combining** → ω Meson Finder Tree

ω Meson Finder Tree → **Event Skimming** → Exclusively Skimmed Events with ω Meson → Root Tree Ntuple Analysis → Histograms and Plot Making

- Current workflow is based on the blue blocks
- Slurm job submission workflow is designed
- Takes 1 hour to process the entire workflow
- Can go upper stream on Input decoded datasets to compare different AI tracking models

Channel	**PiPi_Torus+1.root**	**Gamma_Torus+1.root**
Bending	**PiPi_Torus-1.root**	**Gamma_Torus-1.root**

Data Inputs and Output and General Statistics

- Currently, I have been focusing on RGA Fall 2018 Pass 2 hipo DST Datasets on JLab ifarm

	Number of files in Tape (/mss)	Final Skimmed Files Processed	Percent Processed
Torus-1	24838	24417	98.3%
Torus+1	31260	21956	70.2%
Total Fall 2018	56098	46373	82.7%

	Estimated in Events Tape (/mss)	Estimate Events Processed	Percent Processed
Torus-1	87.4 billion	85.9 billion	98.3%
Torus+1	84.0 billion	59.0 billion	70.2%
Total Fall 2018	171.4 billion	144.9 billion	82.7%

- Statistics is not yet complete
- Will include Spring 2018 and Spring 2019 datasets

Data Analysis

# Inclusive $\pi^0 \to \gamma\gamma$ Reconstruction
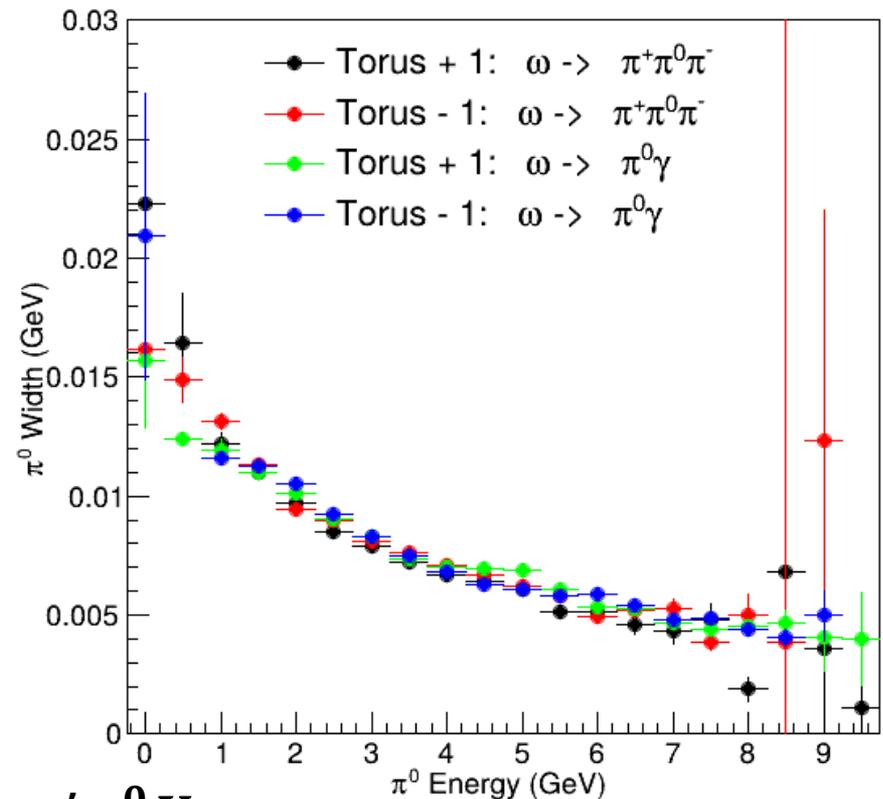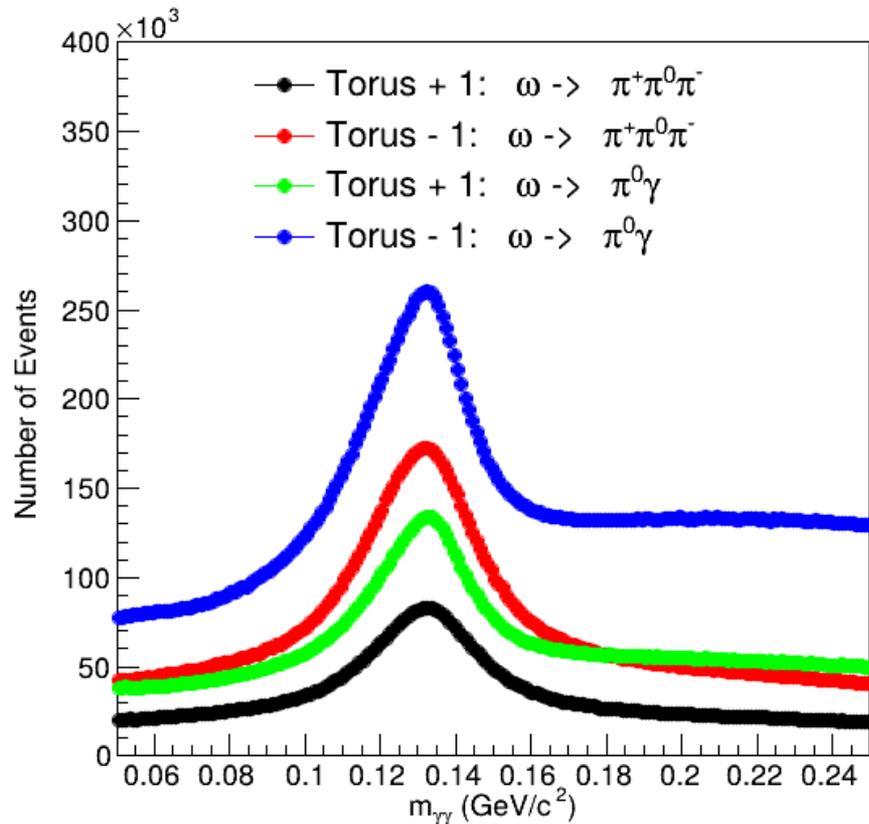
$$ep \to e'\pi^0 X$$

- Huge statistics for inclusive π^0 events for both Torus+1 and Torus-1
- Impose a cut on and enforce the mass of $0.11 < m_{\gamma\gamma} < 0.16$ GeV/c^2 to be 0.135 GeV
    - Potential optimization: is to include E dependent cut on the width to label as π^0
    - Force the region to be 0.135 GeV mass
- Possibly may be use as a skim in the DST hipo level

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Channel 1

$$\omega \rightarrow \pi^+ \pi^- \pi^0$$

BR = 89.2%

$\omega \to \pi^+\pi^-\pi^0$ Reconstruction Before Cuts
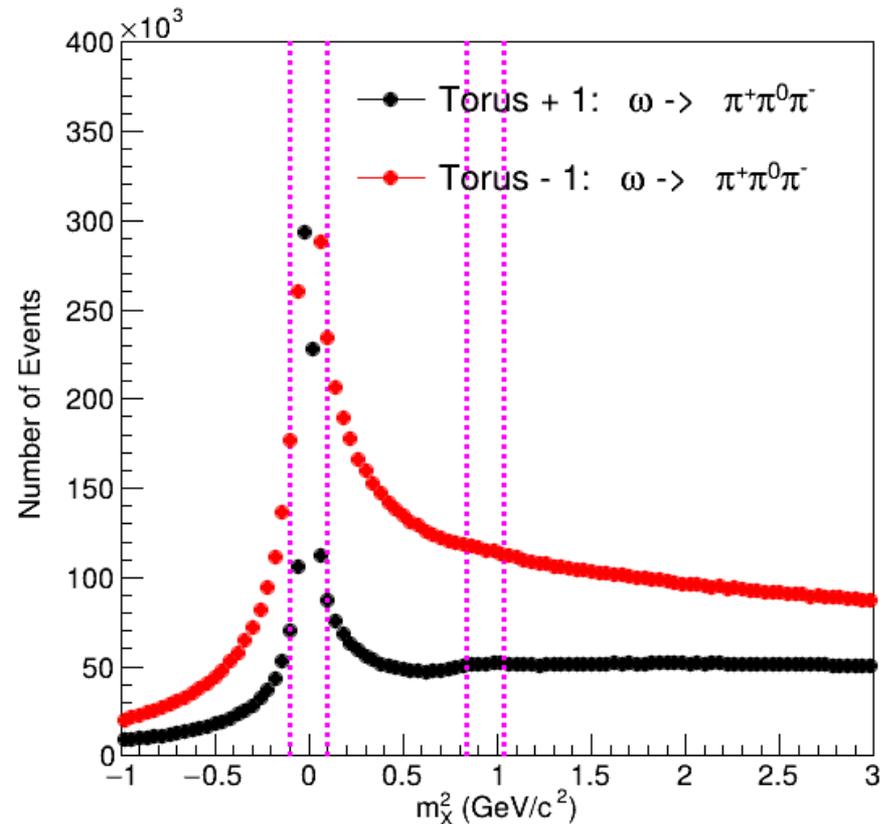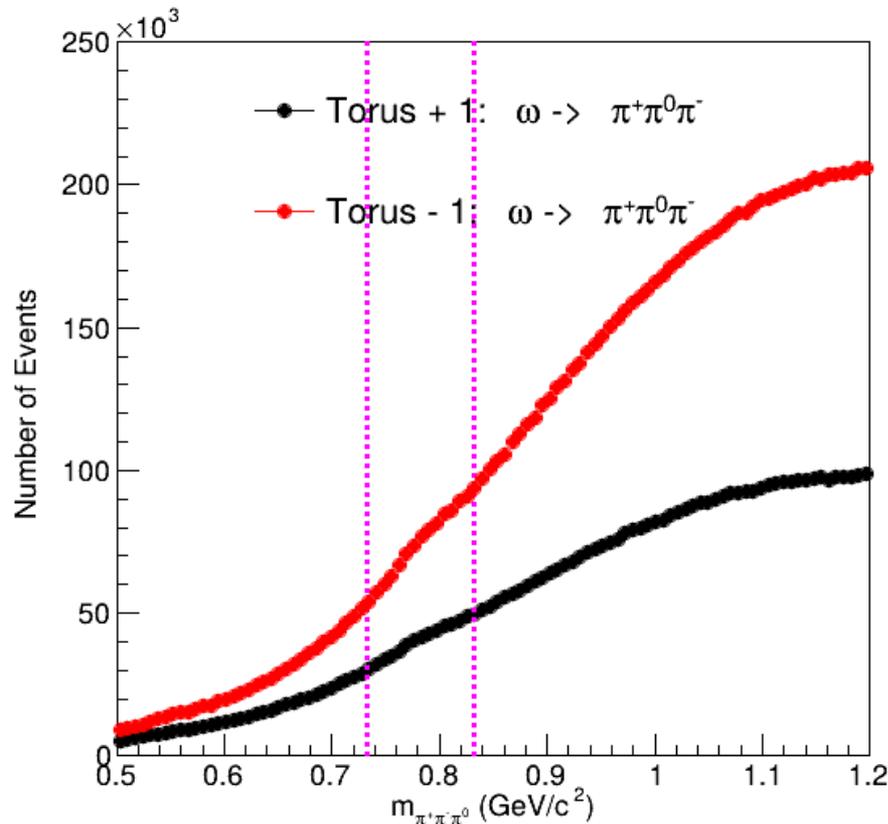
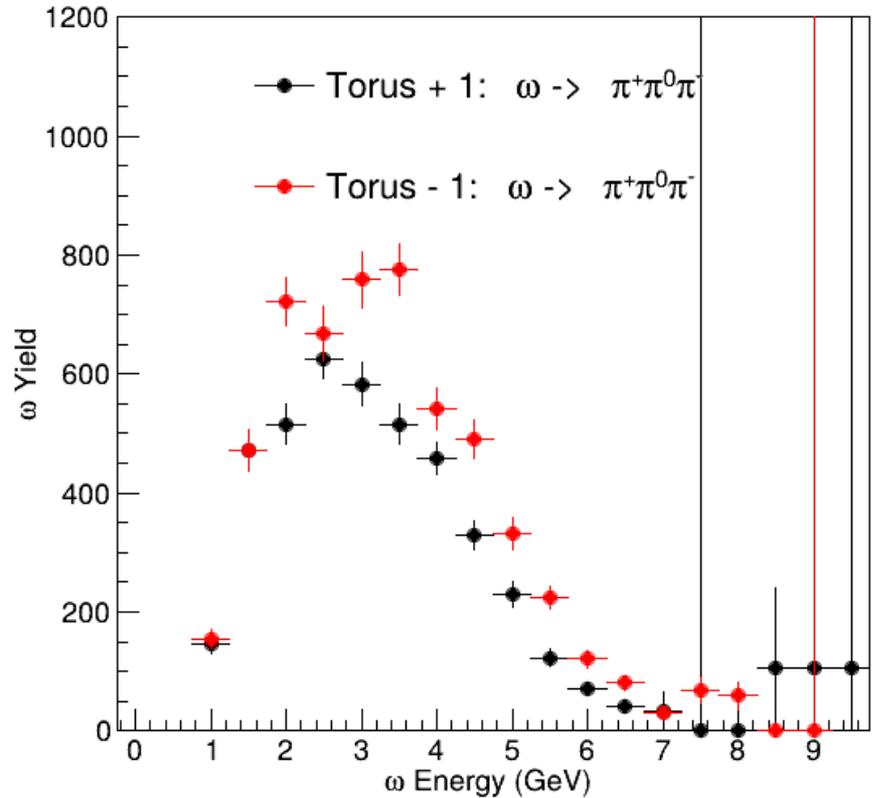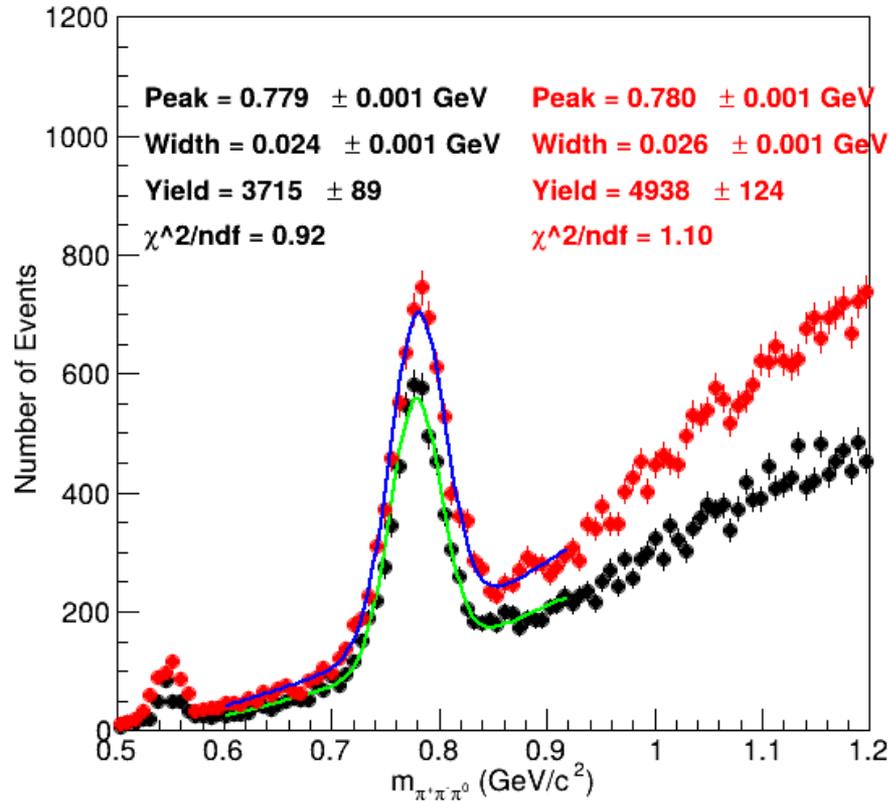- Require exactly 1 electron and no other particles than π^+, π^-, p, and γ in the DST event builder PID
- A hint of $\omega(782)$ see in both cases with different statistics
- Use the missing mass on m_X^2 on p, π^+, π^-, and π^0 as cuts to improve the yields
  - Alternatively other decay topological variables like momentum and opening angles

Proton Missing Mass Studies
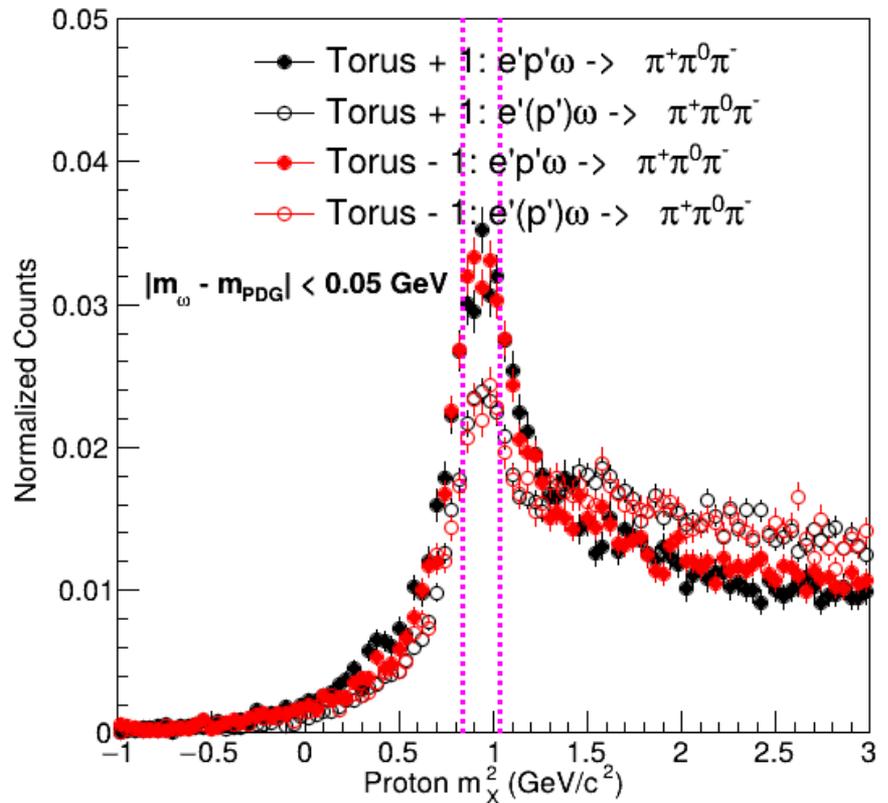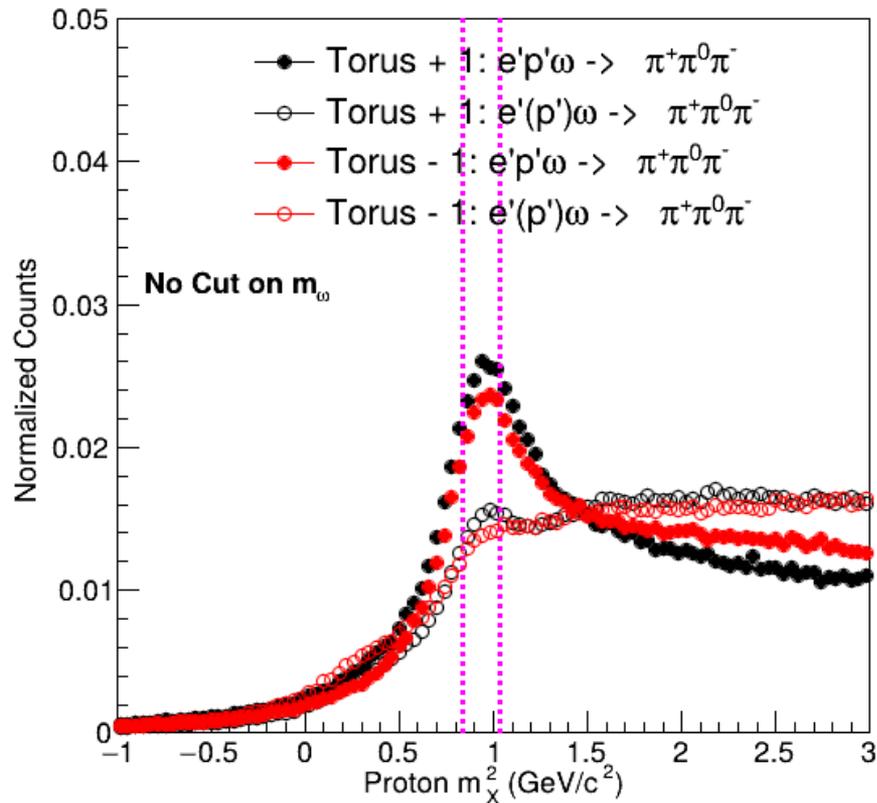
- Define a cut width of 0.1 GeV on the proton m_X^2 and extract the ω yield instead
- Similar shape between m_X^2 with 1 proton (solid circles) and 0 proton (open circles) after cuts with a peaking structure near the mass of proton at 1 GeV
- Exclusivity confirmed and m_X^2 for proton works
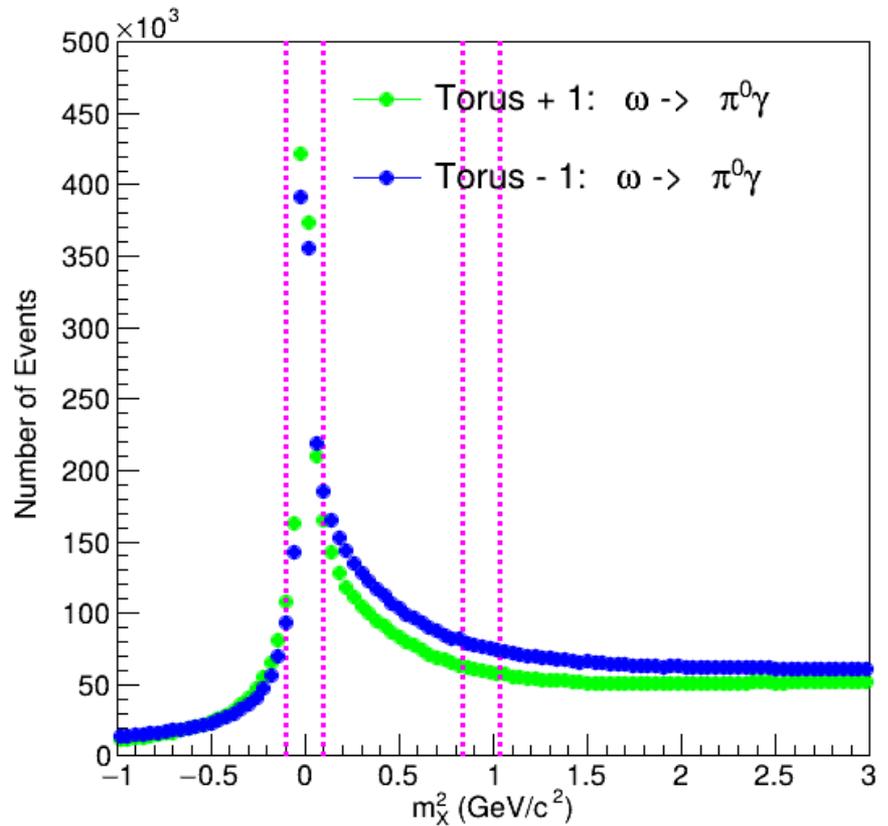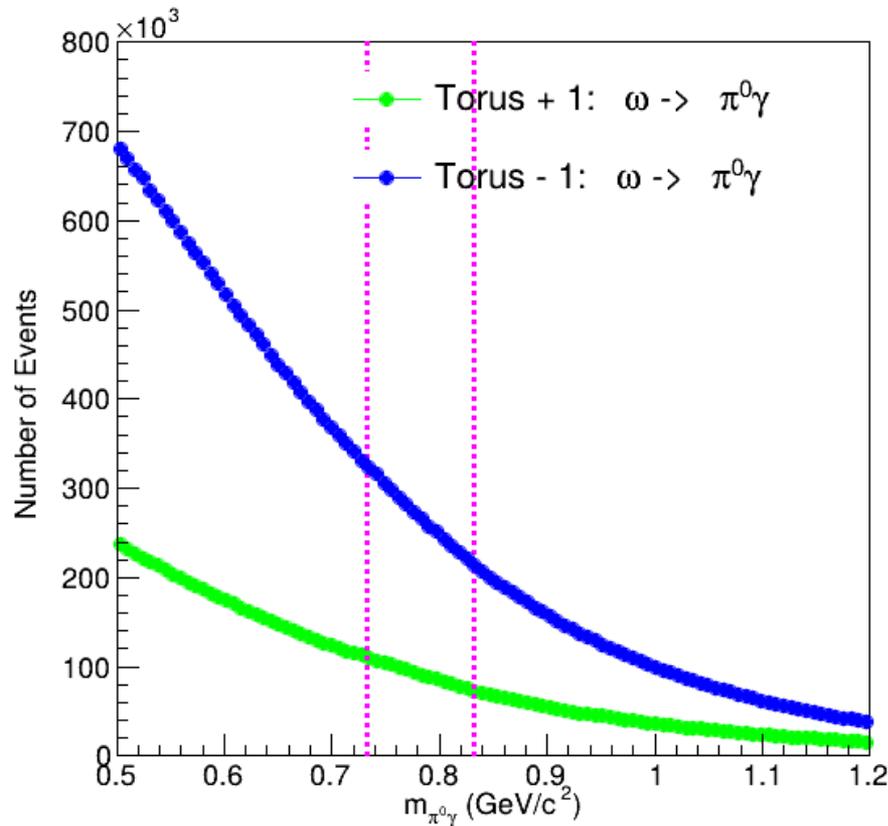
Application of Cuts on ω

- Model: Single Gaussian + Quadratic background
- Good statistics overall ~10000 combined together
- ω yield enhancement: topological cuts and consider missing pions
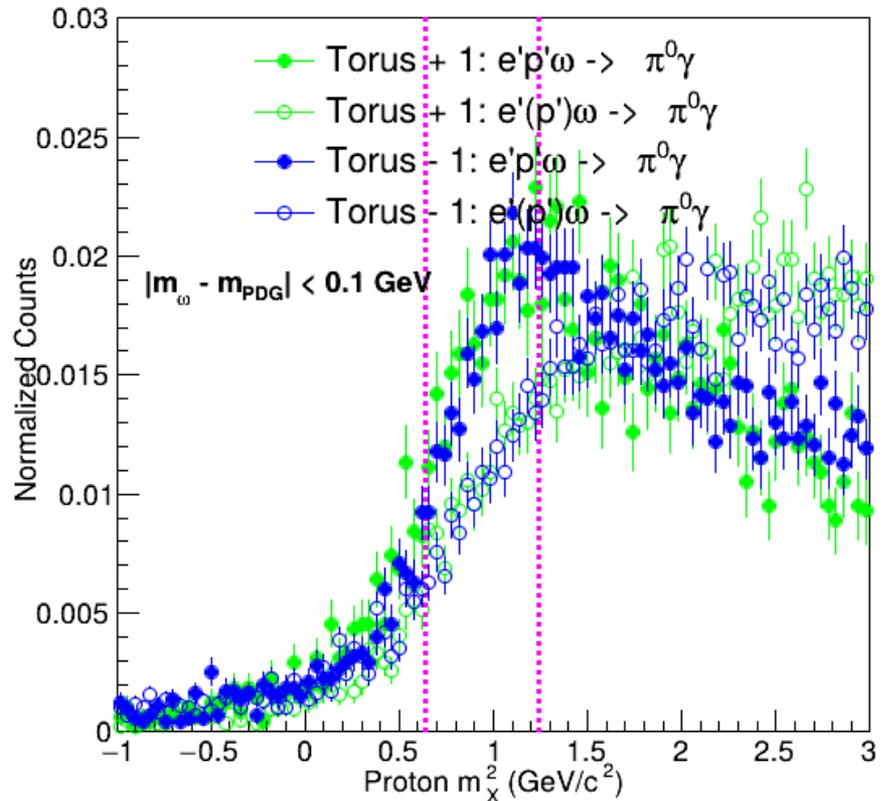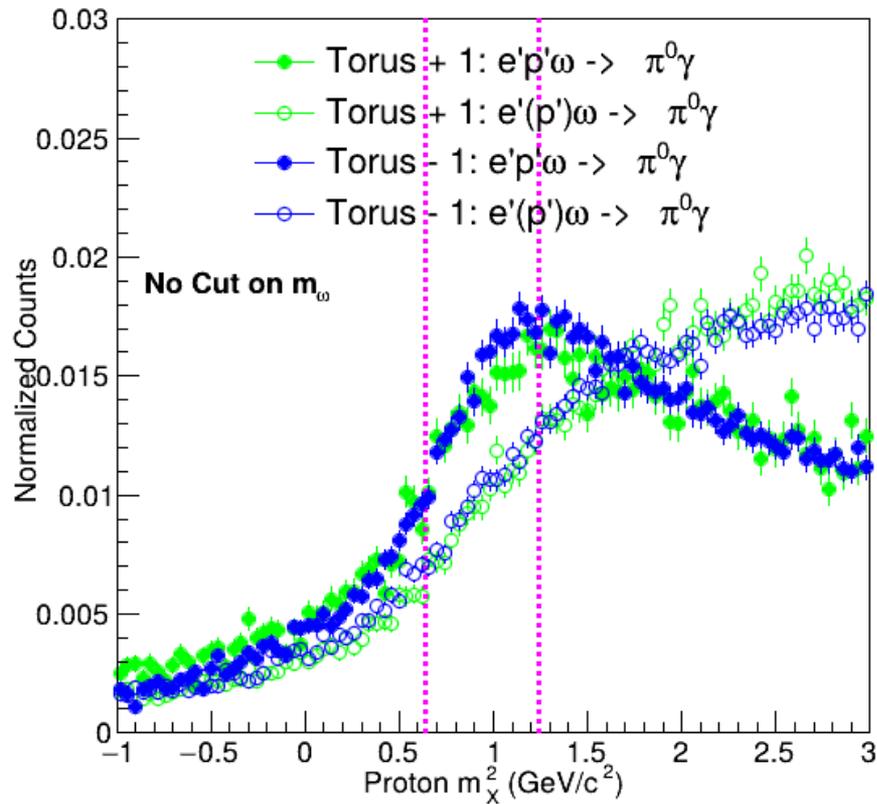
Channel 2

$$\omega \rightarrow \pi^0 \gamma$$

BR = 8.33%

# $\omega \rightarrow \pi^0\gamma$ Reconstruction

- Require exactly 1 electron and no other particles than p, and γ in the DST event builder PID and and existing cluster energy $E_\gamma > 0.8$ GeV requirement for the three phtons
- Use the missing mass on m_X^2 on protons p and π^0 as cuts to improve the yields

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Proton Missing Mass Studies

- Cutting on ω and m_X mutually create no peaks
  - Even after tighten the cuts
  - No yet fully exclusive in this case when a proton is missing
  - Need to check backgrounds

Exclusive ω Reconstruction with Cuts
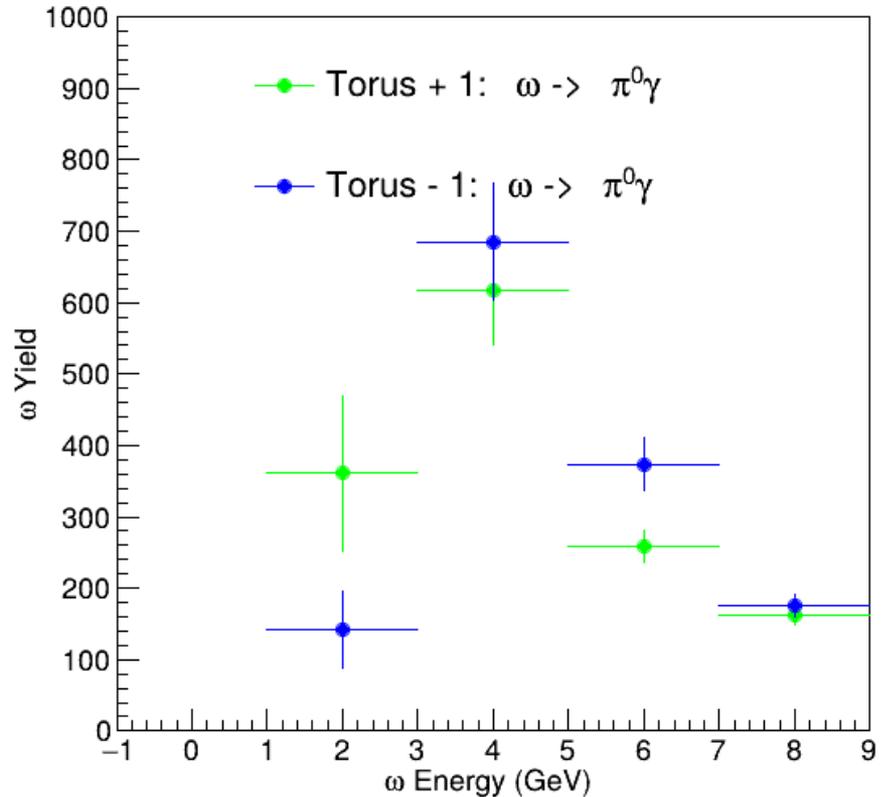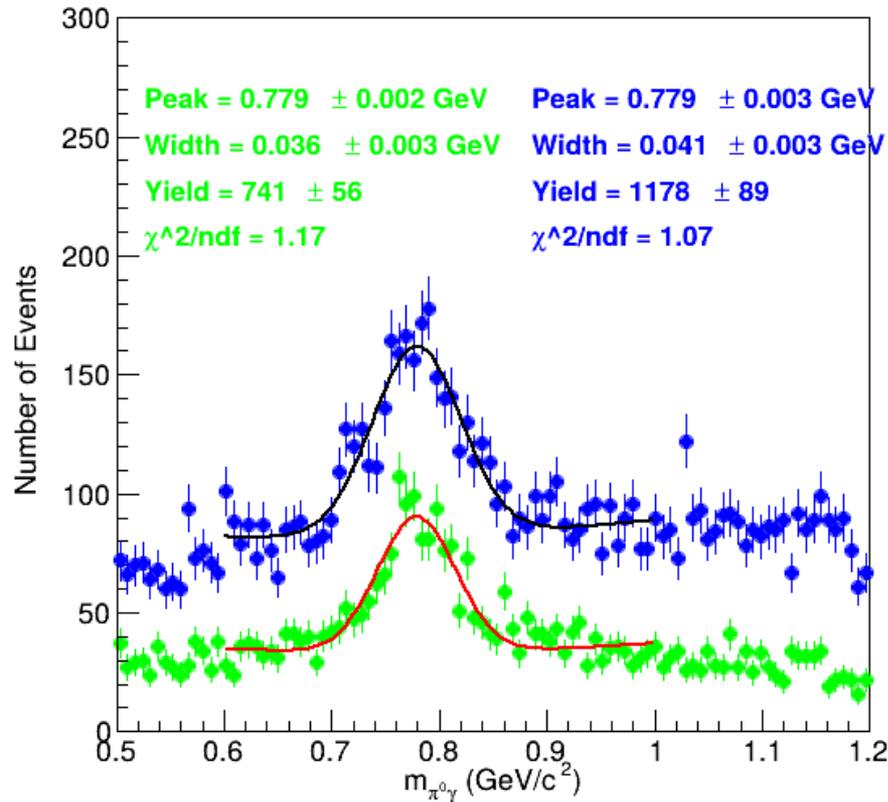
- Backup channel: overall good ω yield
- $\omega \to \pi^0\gamma$ yield is more that 10% of the $\omega \to \pi^+\pi^-\pi^0$ channel, which does not scale with the BR
- The width is wider than the $\omega \to \pi^+\pi^-\pi^0$ channel because of the resolution of the ECAL compared to the tracker
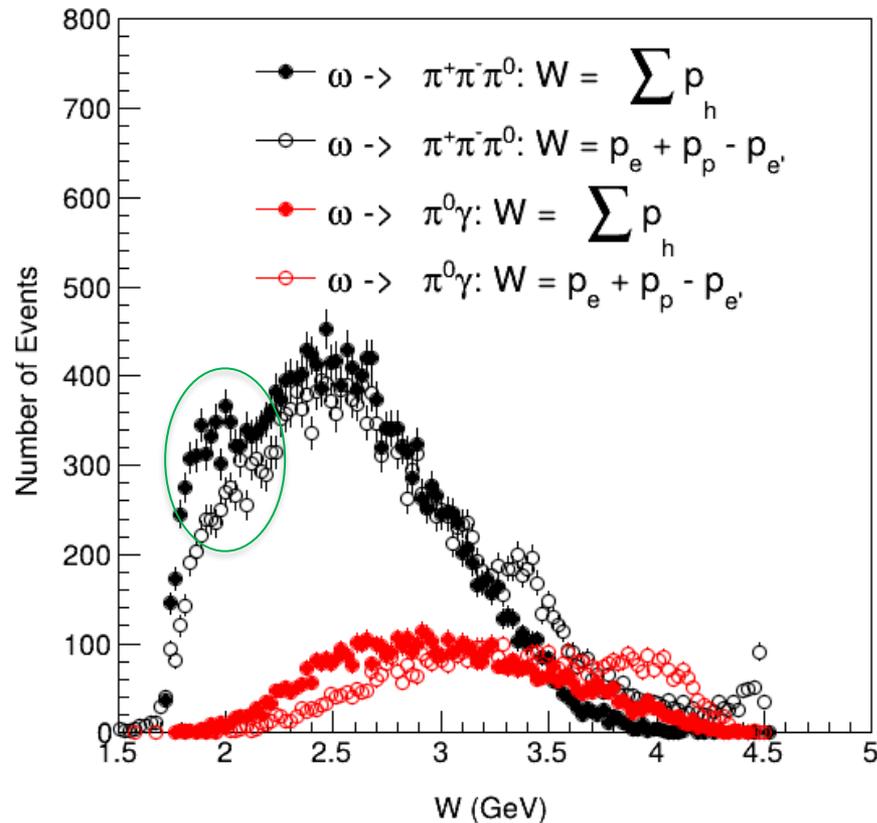
Missing Particle Summary

Channel	Missing Particles	Missing Mass Cut m_X^2 (GeV^2)
$\omega \to \pi^+\pi^-\pi^0$	$ep \to e'p'\omega$	$\left\| m_X^2 - m_p^2 \right\| < 0.1$
	$ep \to e'(p')\omega$	$\left\| m_X^2 - m_p^2 \right\| < 0.1$
	$ep \to e'p'\omega \to \pi^+\pi^-(\pi^0)$	$\left\| m_X^2 - m_{\pi^0}^2 \right\| < 0.01$
	$ep \to e'p'\omega \to \pi^+(\pi^-)\pi^0$	$\left\| m_X^2 - m_{\pi^-}^2 \right\| < 0.01$
	$ep \to e'p'\omega \to (\pi^+)\pi^-\pi^0$	$\left\| m_X^2 - m_{\pi^+}^2 \right\| < 0.01$
$\omega \to \pi^0\gamma$	$ep \to e'p'\omega$	$\left\| m_X^2 - m_p^2 \right\| < 0.1$
	$ep \to e'(p')\omega$	$\left\| m_X^2 - m_p^2 \right\| < 0.1$
	$ep \to e'p'\omega \to (\pi^0)\gamma$	$\left\| m_X^2 - m_{\pi^+}^2 \right\| < 0.01$
	$ep \to e'p'\omega \to \pi^0(\gamma)$	$\left\| m_X^2 \right\| < 0.01$

- Current sample explicitly require all pions to be reconstructed
- Will need to look at the extra ω yield gain from working on pion missing masses
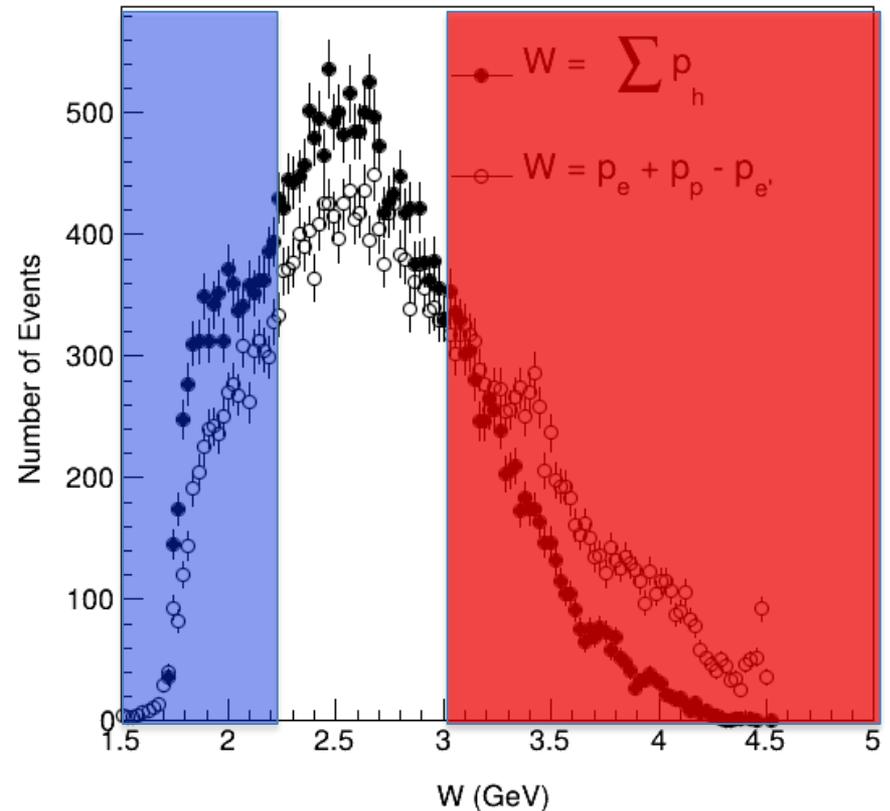- I am combining the inbending and outbending data at this point

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Physics Studies

All Combined Comparison

W Distributions

Legend:
- $\omega \to \pi^+\pi^-\pi^0: W = \sum_h p_h$
- $\omega \to \pi^+\pi^-\pi^0: W = p_e + p_p - p_{e'}$
- $\omega \to \pi^0\gamma: W = \sum_h p_h$
- $\omega \to \pi^0\gamma: W = p_e + p_p - p_{e'}$

Combined Channel W Distributions



Legend:
- $W = \sum_h p_h$
- $W = p_e + p_p - p_{e'}$

- Combined inbending and outbending for each channel
- Different kinematics region for different decay channels
- Consistency between two methods for calculating W
- A small structure seen below 2.2 GeV for the hadronic method
  - ω, π^0, and p are all forced to PDG mass values within the signal region

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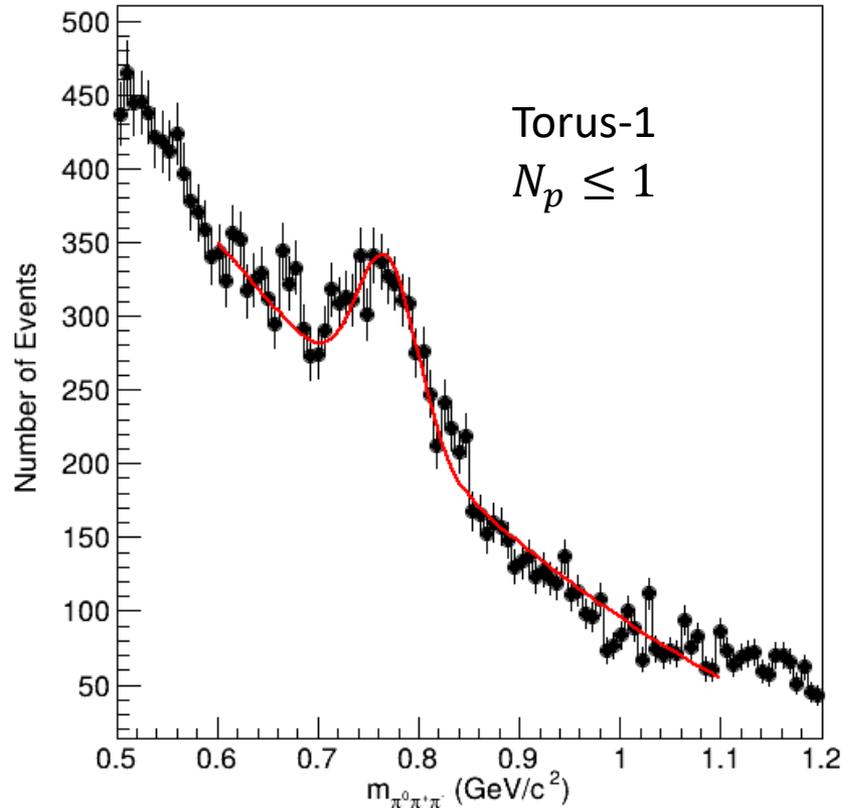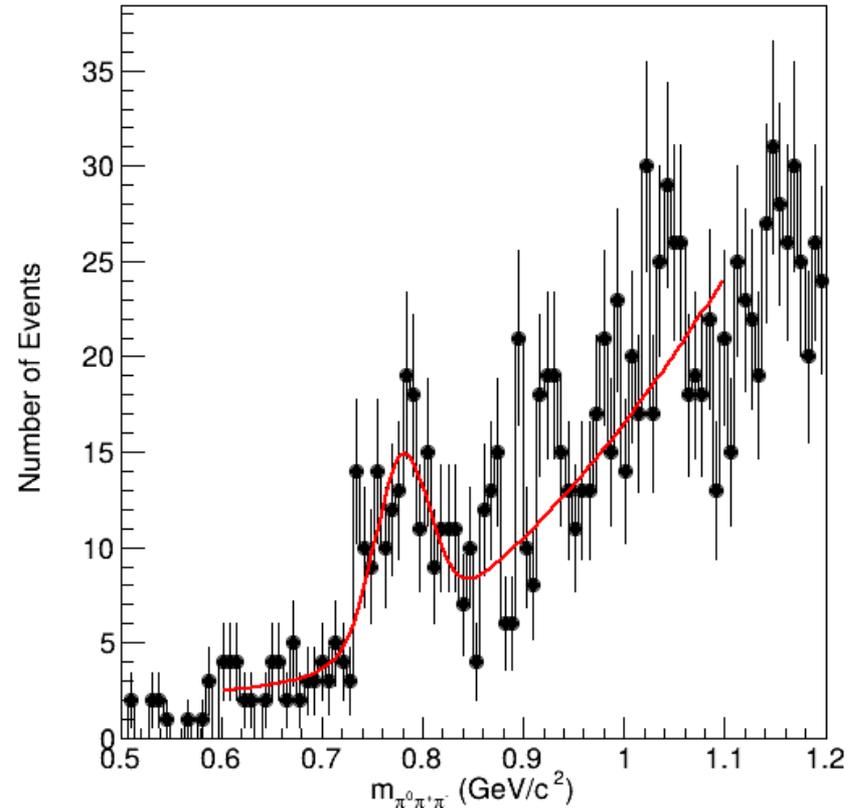# Example Fit at Small and large Q^2

Kinematic Range: $0.0 < Q^2 < 0.6$
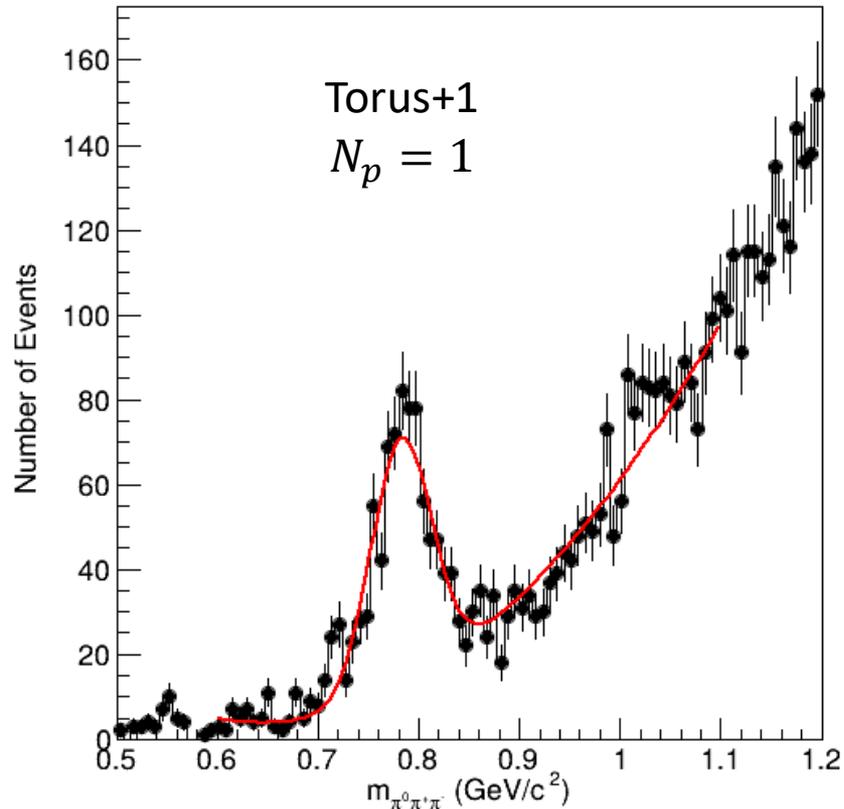
Kinematic Range: $3.6 < Q^2 < 4.2$
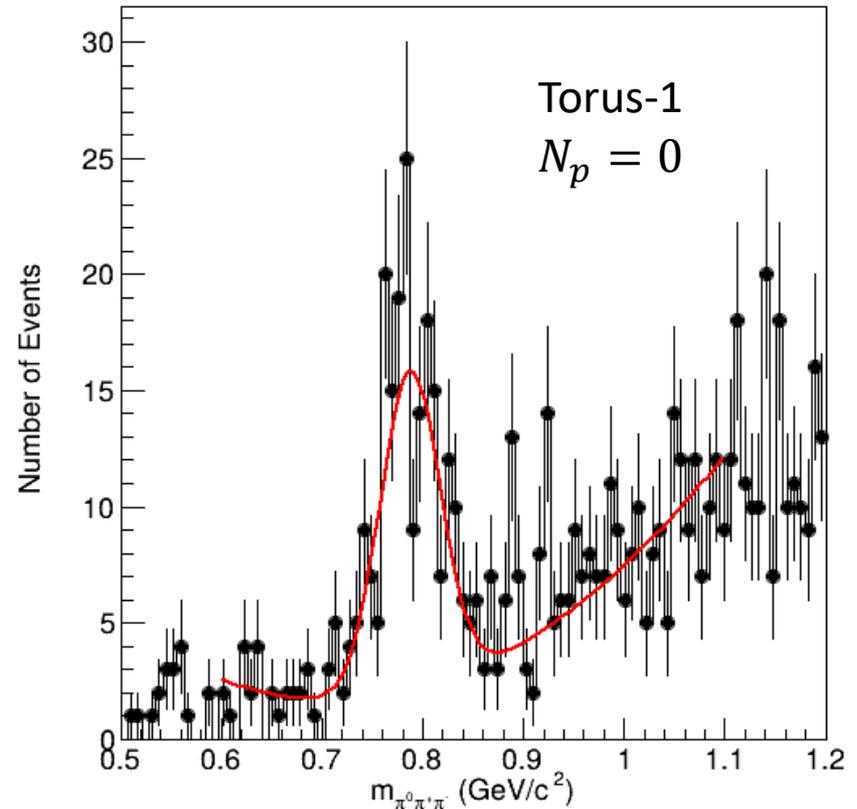
Torus+1
$N_p = 1$

Torus-1
$N_p = 0$

- $t = (p_{p'}^{\mu} - p_p^{\mu})^2$ and $Q^2 = (p_{e'}^{\mu} - p_e^{\mu})^2$
- Vector Meson Dominance at small Q^2 and t
- Generally good ω yield covering up to $Q^2 > 4$ GeV²

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Example Fit at Small and large $|t|$
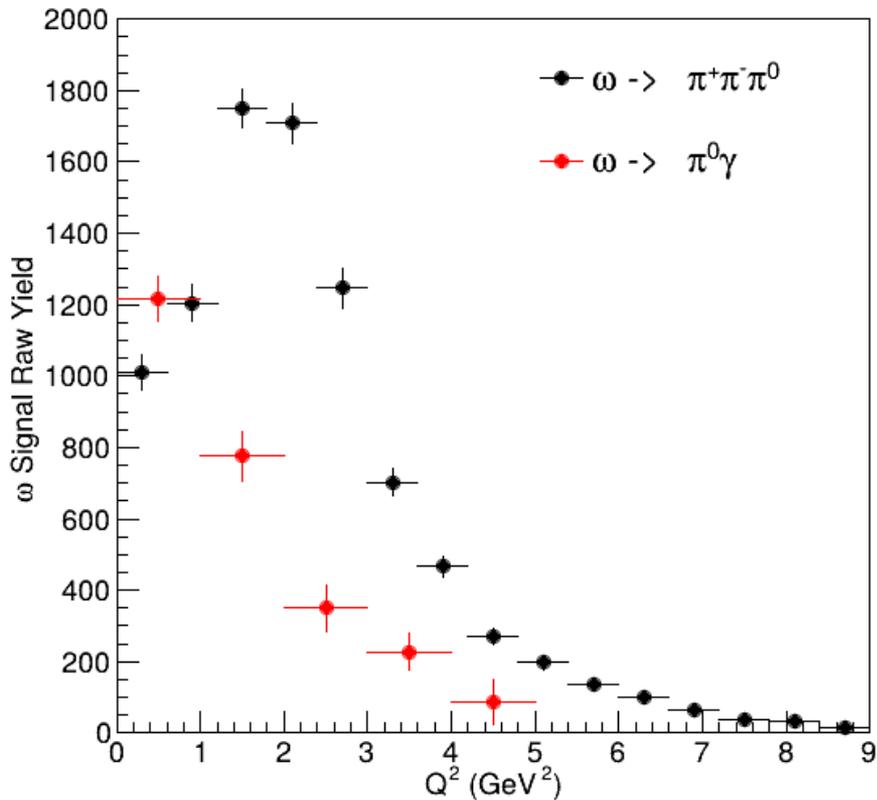

Kinematic Range: $0.0 < |t| < 0.5$

Torus-1
$N_p \leq 1$

Kinematic Range: $3.0 < |t| < 3.6$

- $t = (p_{p'}^{\mu} - p_p^{\mu})^2$ and $Q^2 = (p_{e'}^{\mu} - p_e^{\mu})^2$
- Vector Meson Dominance at small Q^2 and t
- Generally good ω yield covering up to $Q^2 > 3$ GeV^2

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ω Combined Channels: Q^2 and $-|t|$ Statistics

ω Yield vs Q^2 for Combined In and Outbending

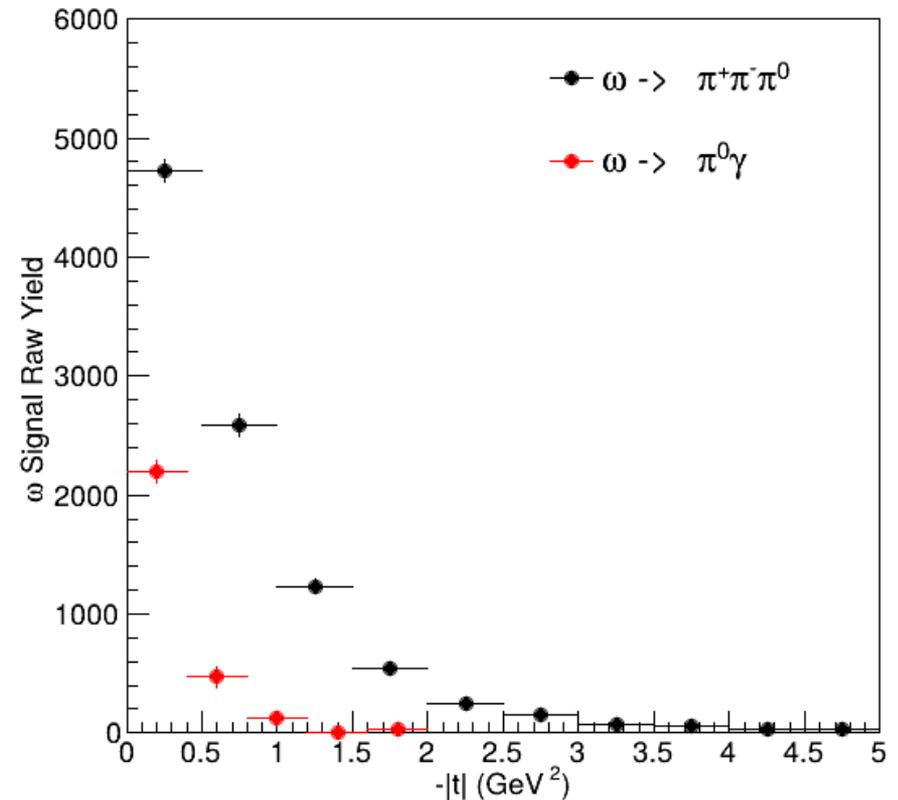### ω Yield vs $-|t|$ for Combined In and Outbending


- $t = (p_{p'}^{\mu} - p_p^{\mu})^2$ and $Q^2 = (p_{e'}^{\mu} - p_e^{\mu})^2$
- Vector Meson Dominance at small t
- Generally good ω yield covering up to $Q^2 > 5$ GeV² and $|t| > 2.5$ GeV²

ω Meson Cut Optimization Plan

- Estimate the expected yield (S) and background (M)
  - Signal from theoretical calculations + existing data fit: S
  - (Uncorrelated) background from sideband/mixed events: B
    - Reference to Talk AI package for $\omega \to \pi^0 \gamma \to \gamma\gamma$
  - Develop ML based topological cuts on the ω meson with TMVA or other ML/AI toolkits for signal significance $\frac{S}{\sqrt{S+B}}$

- AI/ML training Implementation
  - Identify a set of topological variables for optimization
  - Data/MC Validation for topological variables
    - sPlot techniques on the signal vs sideband method
  - Perform traditional cut base analysis
  - Train ML models and compare performance (ROC curve)
  - Find the optimal working point

- MC Samples Generation
  - Omega generator with OSG
  - Reweight on Q^2 and x with model/published data driven $\frac{d^2\sigma}{dx\,dQ^2}$
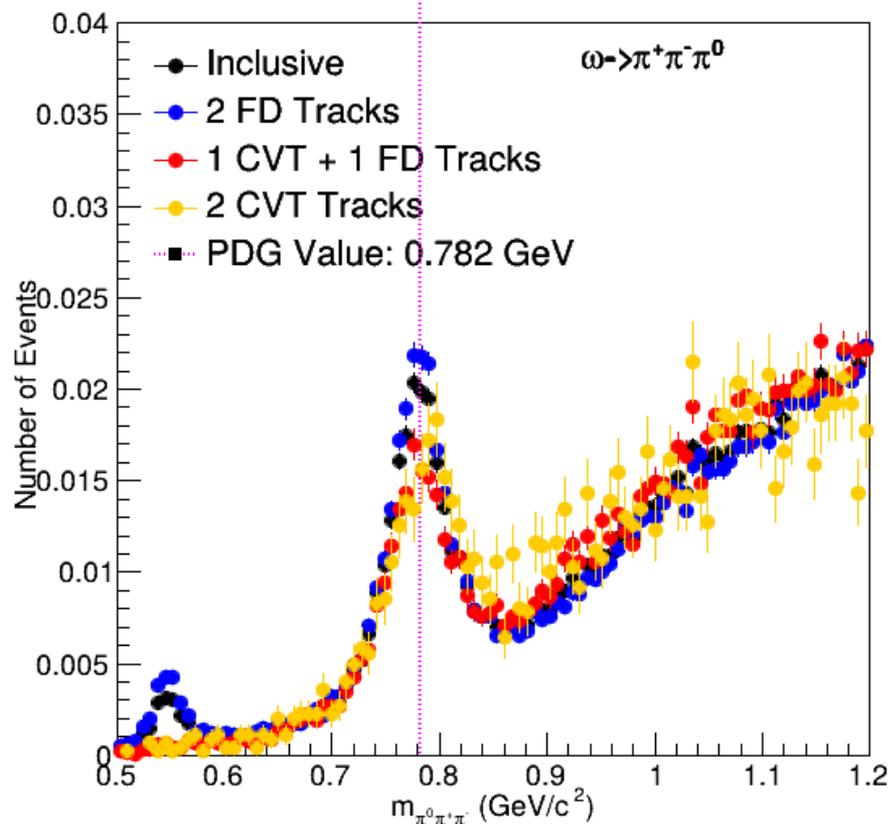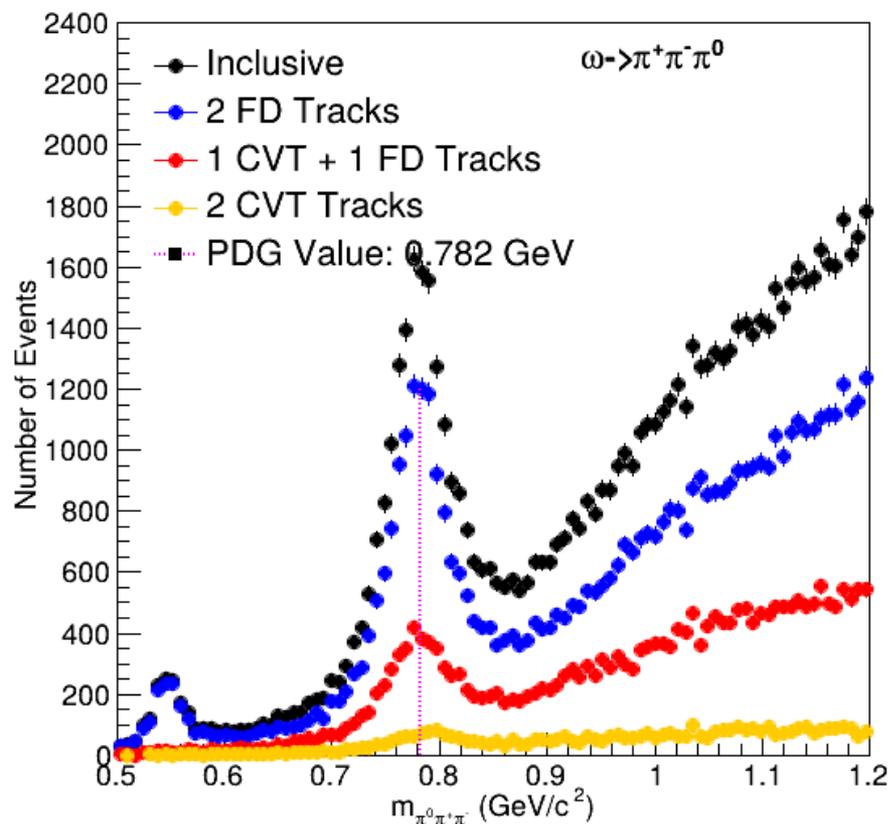
- Slight off ω calibration from 782 GeV the CVT compared to the FD for Pass 2
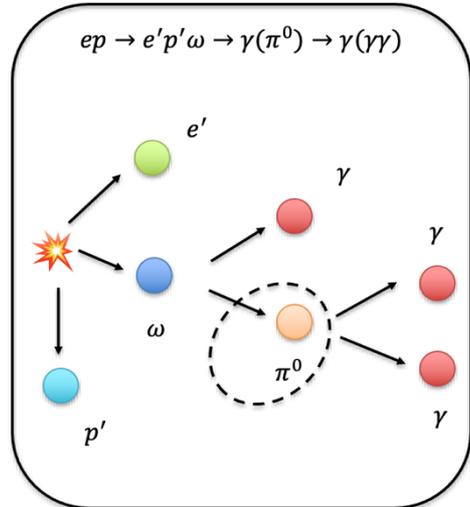- Should investigate the missing mass of π^0

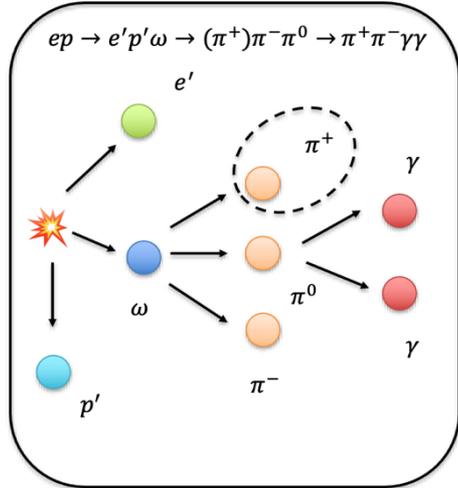# Extra: Peak Qualities
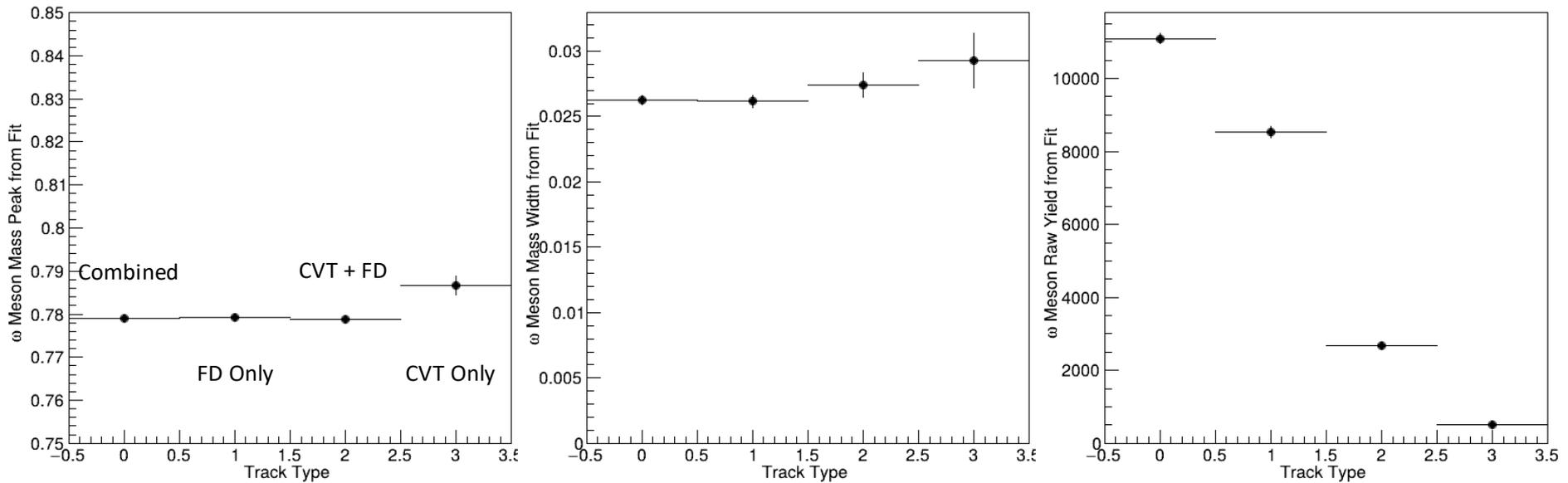
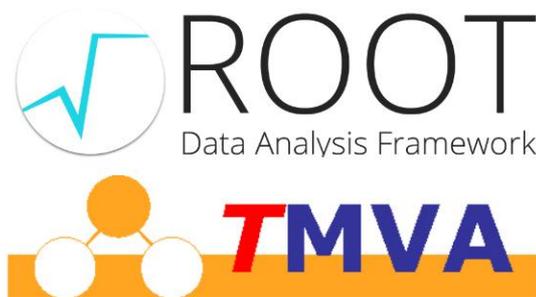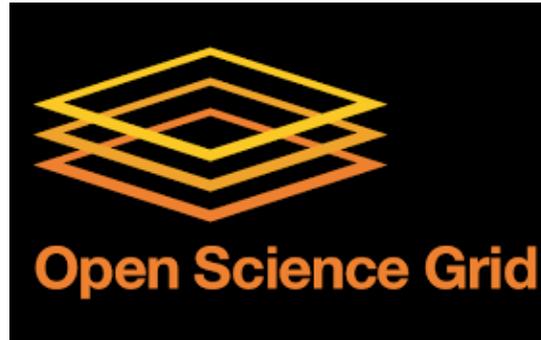- Peak: only shifted by ~5 MeV by the CVT only tracks
- ω width of the CVT only π tracks is slightly worse
- The ω yield with CVT only track is low because of the kinematics
  - Tracking efficiency effect?
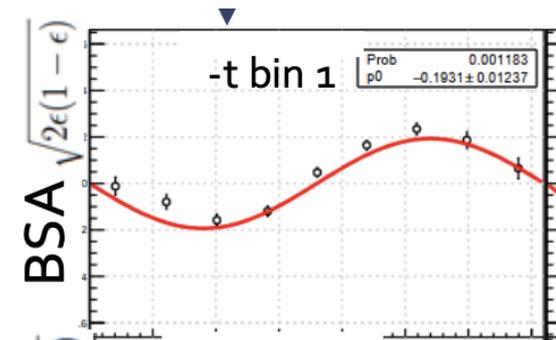
ω Analysis To Do List

Include Missing Pions to Enhance the ω Yield

$$ep \rightarrow e'p'\omega \rightarrow (\pi^+)\pi^-\pi^0 \rightarrow \pi^+\pi^-\gamma\gamma$$

$$ep \rightarrow e'p'\omega \rightarrow \gamma(\pi^0) \rightarrow \gamma(\gamma\gamma)$$

MC Generation and ω Yield Optimization

Open Science Grid

ROOT
Data Analysis Framework

TMVA

Efficiency Correction and Physics Measurements

(BW + P1) fit to the sum of the 2^{++} and BG intensities

χ^2 / ndf   51.81 / 18
p0   1.802e+05 ± 8792
p1   1.297 ± 0.007591
p2   0.1259 ± 0.01279
p3   0 ± 0
p4   1.068e+04 ± 5952
p5   2110 ± 1.075e+04

Tot: 26084; BW: 22886; BG: 3197

m ($\pi^+\pi^+\pi^-$) [GeV]

-t bin 1   Prob   0.001183
p0   -0.1931 ± 0.01237
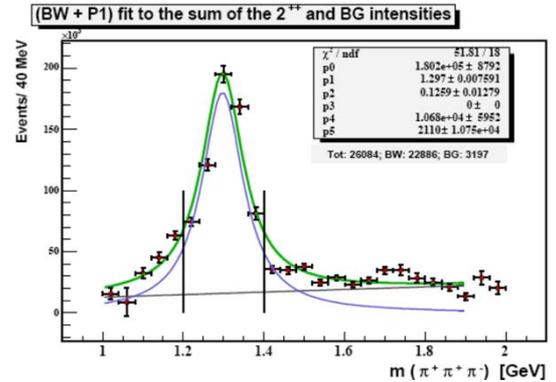
$$\sigma_{LT'}^{sin\Phi} \sim [\bar{E}_T H + H_T E]$$

Next Steps in Analysis

ω Phase Space

2D Plot: $\omega(782) \rightarrow \pi^+ \pi^- \pi^0$ Yield vs t and Q^2
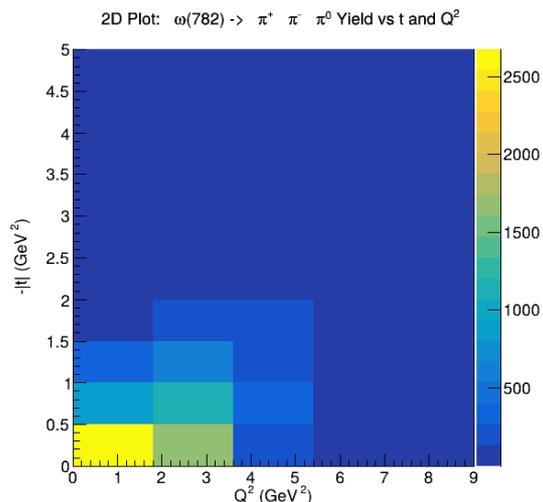
Moving into ω CM frame
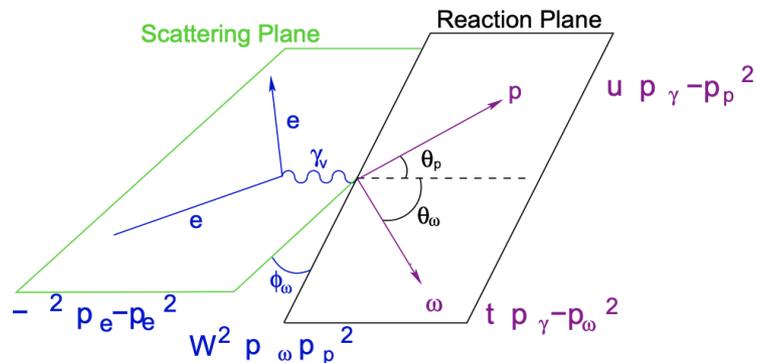
Credit: Wenliang Li's PhD Thesis

$1.7 < W < 2.2$ GeV

(BW + P1) fit to the sum of the 2^{++} and BG intensities

N^*	J^P	Γ (MeV/c^2)	Γ_i/Γ
$N(1700)$	$\frac{3}{2}^-$	$100-200$	$10-34\%$
$N(1710)$	$\frac{1}{2}^+$	$80-200$	$1-5\%$
$N(1720)$	$\frac{3}{2}^+$	$150-400$	$12-40\%$
$N(1875)$	$\frac{3}{2}^-$	$120-250$	$15-25\%$
$N(1880)$	$\frac{1}{2}^+$	$200-400$	$12-28\%$
$N(1895)$	$\frac{1}{2}^-$	$80-200$	$16-40\%$
$N(1900)$	$\frac{3}{2}^+$	$100-320$	$2-13\%$
$N(2060)$	$\frac{5}{2}^-$	$300-450$	$1-7\%$
$N(2100)$	$\frac{1}{2}^+$	$200-320$	$10-25\%$
$N(2120)$	$\frac{3}{2}^-$	$260-360$	$4-20\%$
$N(2190)$	$\frac{7}{2}^-$	$300-500$	$8-20\%$

$$N^* \rightarrow \omega N$$

$W > 2.2$ GeV

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\Phi} = \sigma_T + \epsilon\sigma_L + \epsilon\sigma_{TT}^{cos2\Phi}cos2\Phi + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}^{cos\Phi}cos\Phi + P_b\sqrt{2\epsilon(1-\epsilon)}\sigma_{LT'}^{sin\Phi}sin\Phi$$

$$BSA = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \sim A_{LU}^{sin\Phi}sin\Phi \qquad \boxed{A_{LU}^{sin\Phi} = \sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}^{sin\Phi}}{\sigma_0}}$$

$$\sigma_{LT'}^{sin\Phi} \sim [\bar{E}_T H + H_T E]$$

*Credit: Nicholaus Trotta*

GPD - DVMP

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Conclusions

Summary and To Do List

- **Independent ω Meson Research Program at Lamar with Many Frontiers**
  - Proven feasibility in both $\omega \to \pi^+ \pi^- \pi^0$ and $\omega \to \pi^0 \gamma$ channels
  - High value in terms of hadronic physics: N^* and GPD/TDA
  - Promising future for presentations and publications
  - Potential undergraduate students' involvement

- Major Challenges (time)
  - Time management: need to find lots of time to push the analysis forward
  - Potential ML/AI application → Analysis enhancement by perhaps 50% on the optimized yields: another R&D taking lots of time
  - Need more careful evaluation on the physics
  - Set priorities that aligns with what the CLAS12 needs

- Next Steps in My Mind
  - Create an ω meson proposal with RGA data and go through the CLAS12 review process to make the analysis official
  - Get preliminary results before the end of the summer
    - Cut Optimization, momentum correction, PID, efficiency, systematics …
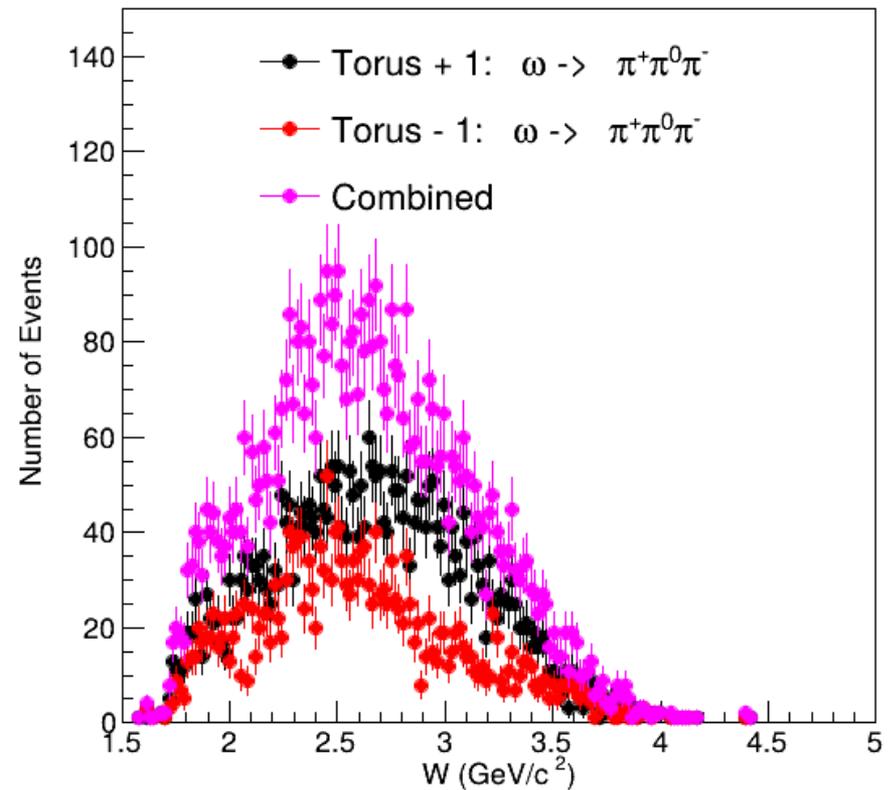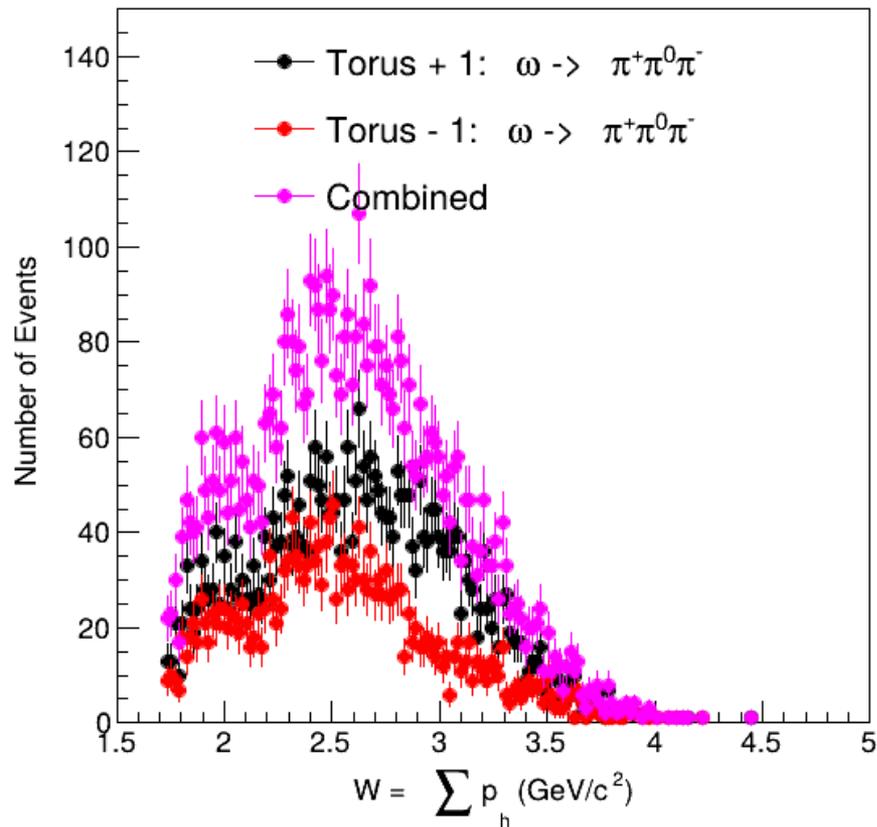 - Prepare for presentation at NSTAR 2026
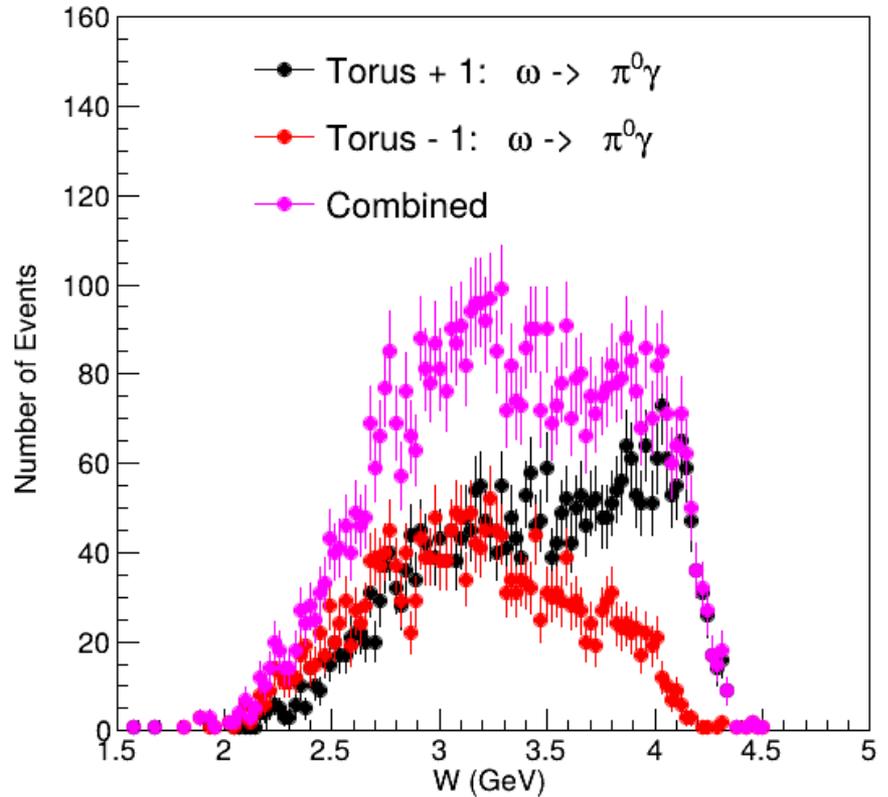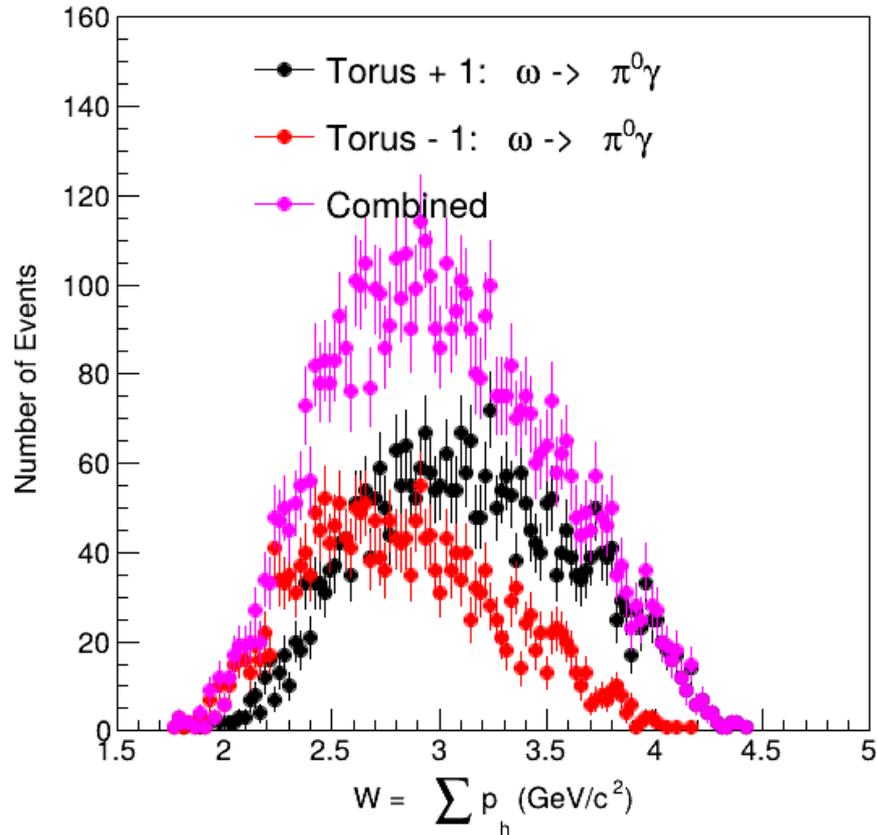
Thank You

ω Yield vs -|t| for Combined In and Outbending
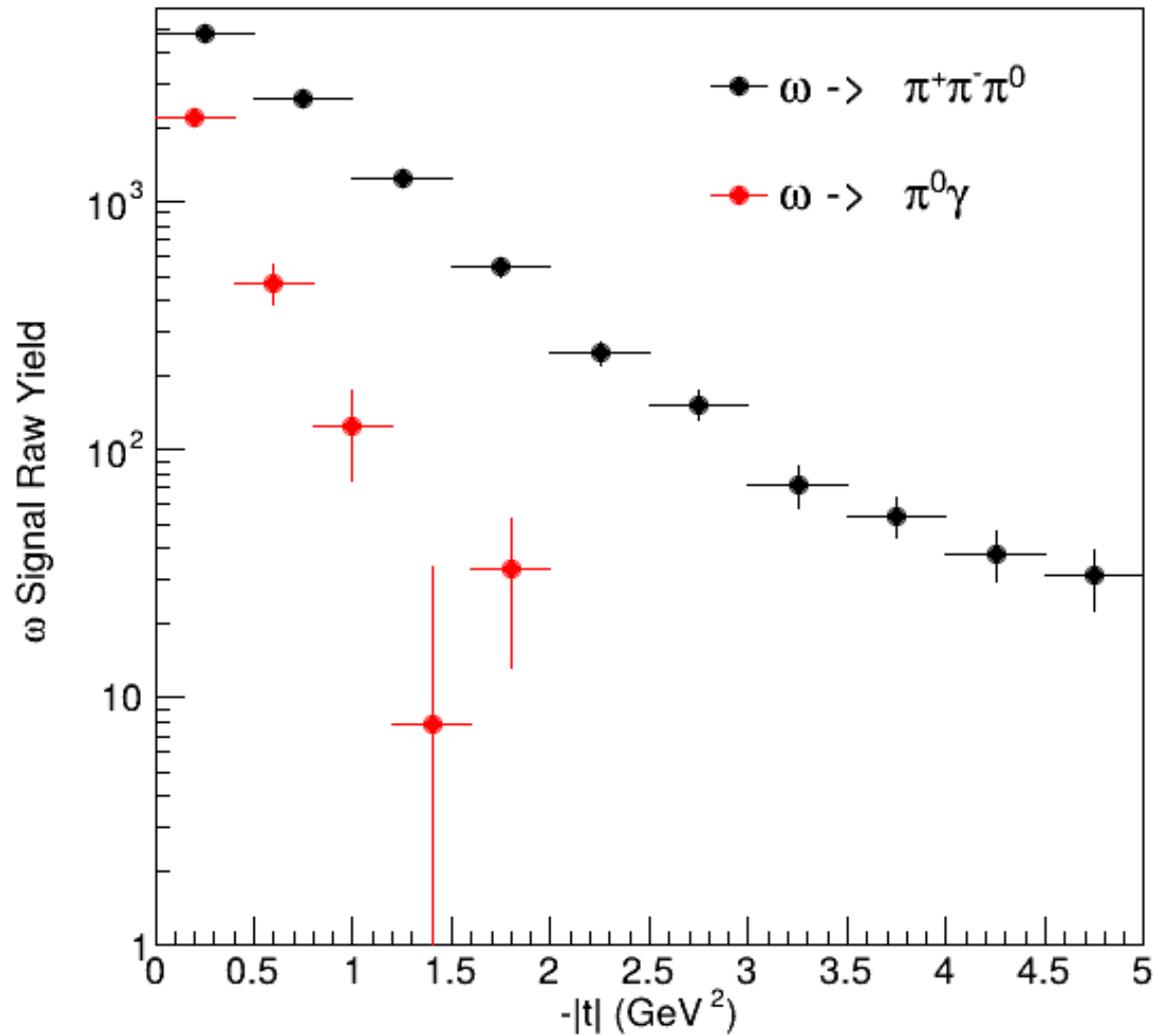
W Distribution for $\omega \to \pi^+\pi^-\pi^0$

- Hadronically (left): forcing the mass of missing proton p and reconstructed $\pi^+\pi^-\pi^0$ with the purple range to their PDG masses (0.938 GeV and 0.782 GeV respectively)
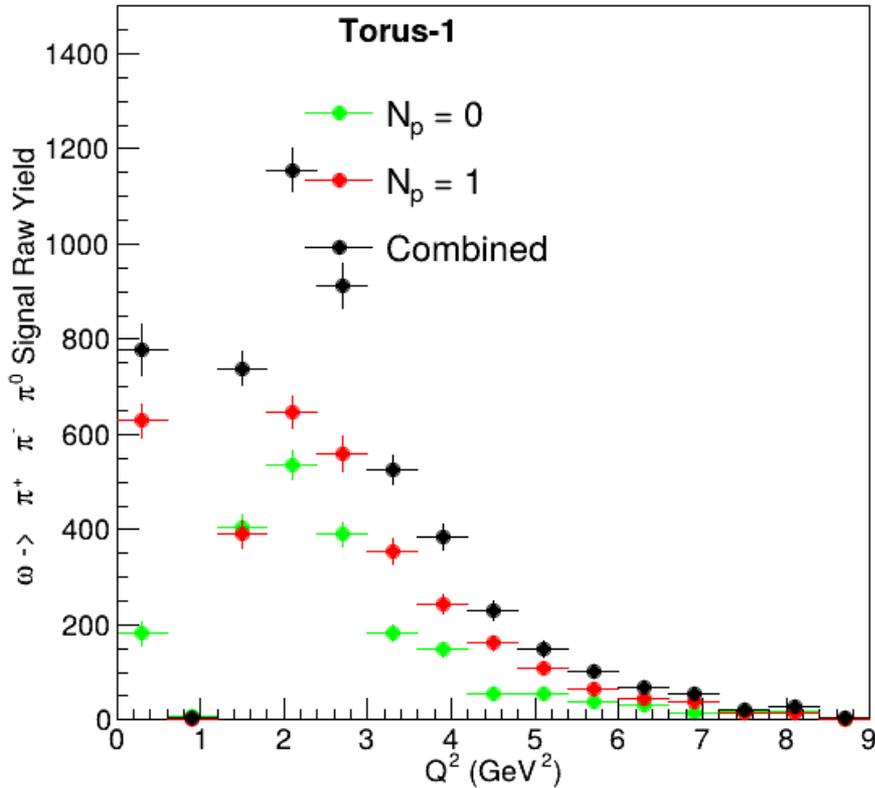- Leptonically (right): $W = |p_e + p_h - p_{e'}|$

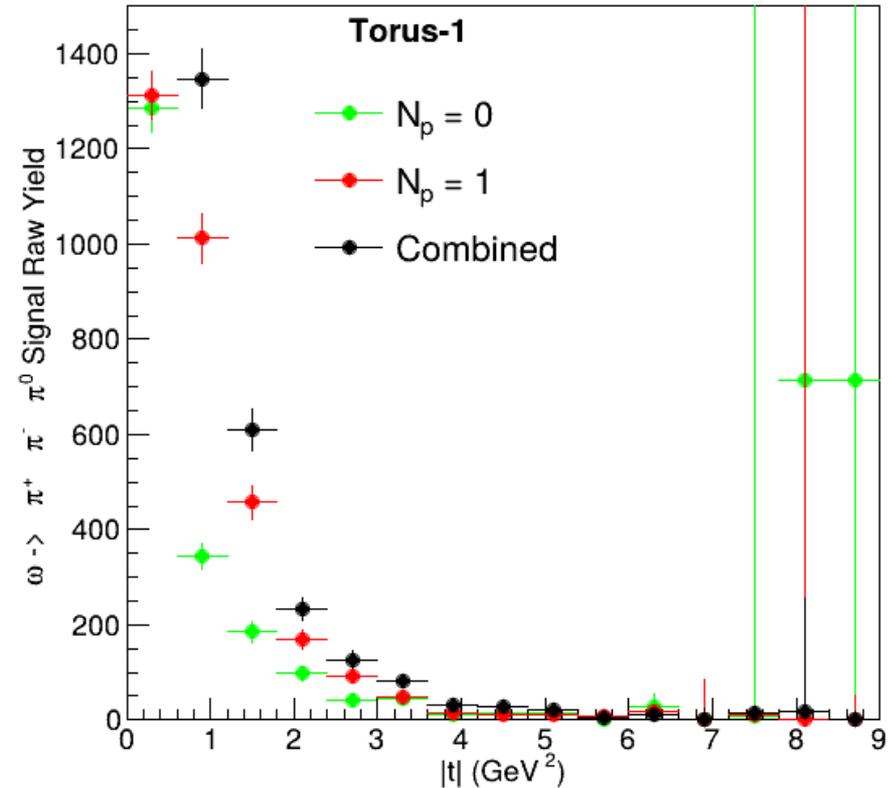# W Distribution for $\omega \rightarrow \pi^0\gamma$

- Inspect the statistics of ω mesons

$\omega \rightarrow \pi^+\pi^-\pi^0$ Yield Statistics: Q^2 Torus - 1

1D Plot: $\omega(782) \rightarrow \pi^+ \ \pi^- \ \pi^0$ Yield vs Q^2
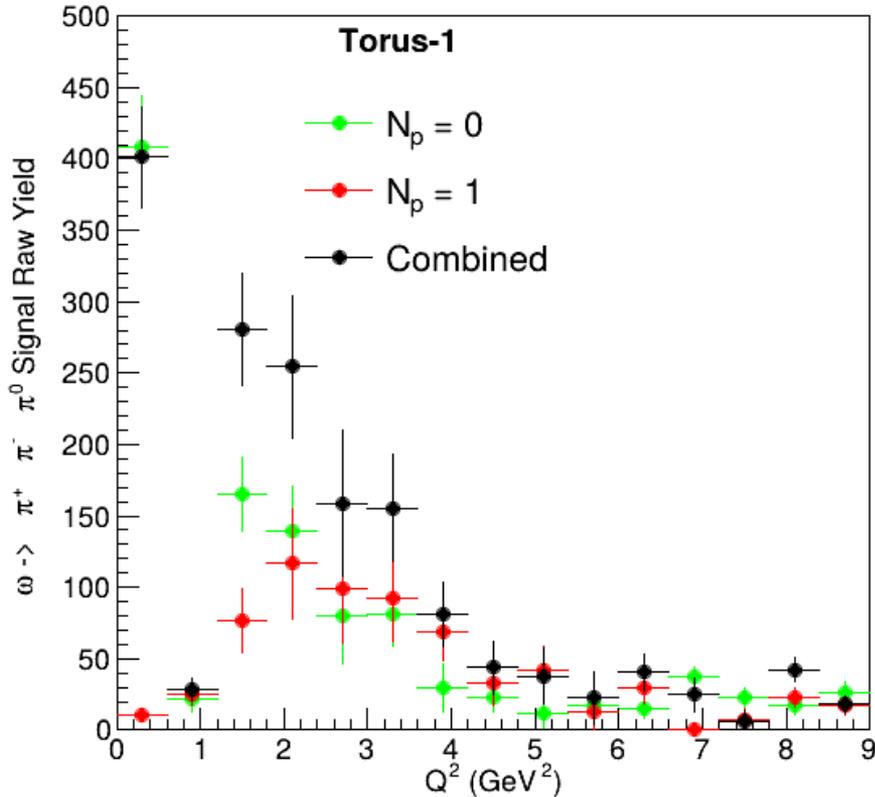
1D Plot: $\omega(782) \rightarrow \pi^+ \ \pi^- \ \pi^0$ Yield vs t

- $t = (p_{p'}^\mu - p_p^\mu)^2$ and $Q^2 = (p_{e'}^\mu - p_e^\mu)^2$
- Vector Meson Dominance at small Q^2 and t
- Generally good ω yield covering up to $Q^2 > 5$ GeV^2 and $|t| > 3$ GeV^2

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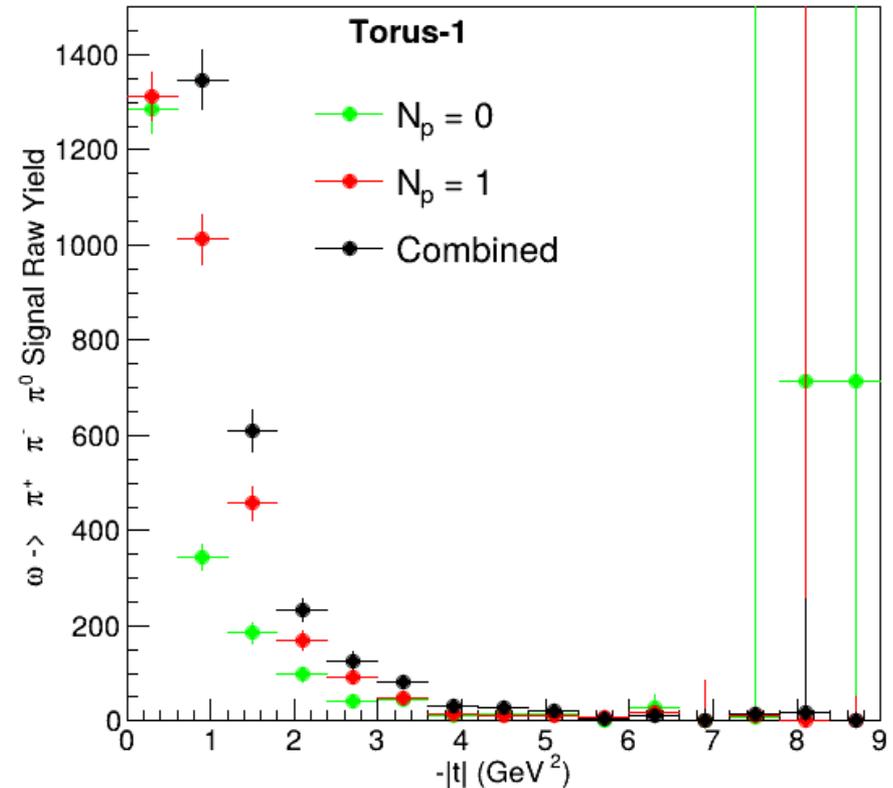# $\omega \rightarrow \pi^0\gamma$ Yield Statistics: Q^2 Torus - 1
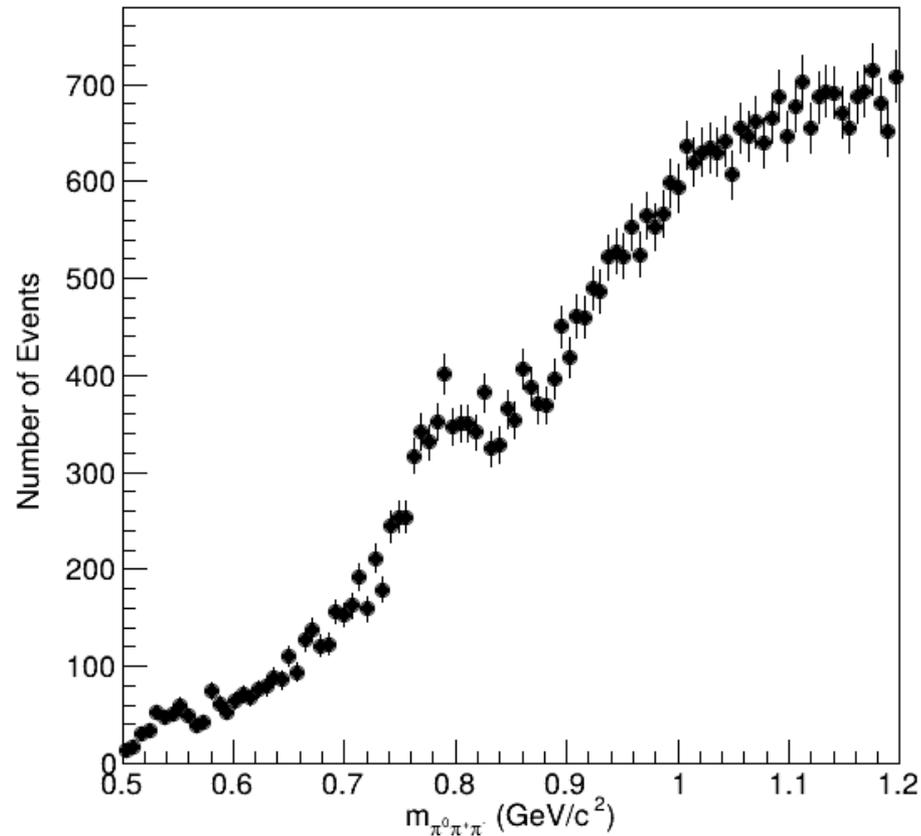

- $t = (p_{p'}^{\mu} - p_p^{\mu})^2$ and $Q^2 = (p_{e'}^{\mu} - p_e^{\mu})^2$
- Vector Meson Dominance at small Q^2 and t
- Generally good ω yield covering up to $Q^2 > 5$ GeV² and $|t| > 3$ GeV²

Fit Plots

$$N_p \geq 2$$

Falsely Identified Protons?

- Why do we have more than 2 protons reconstructed?
  - Likely issue from event builder
  - Look at the missing mass

Falsely Identified Protons?
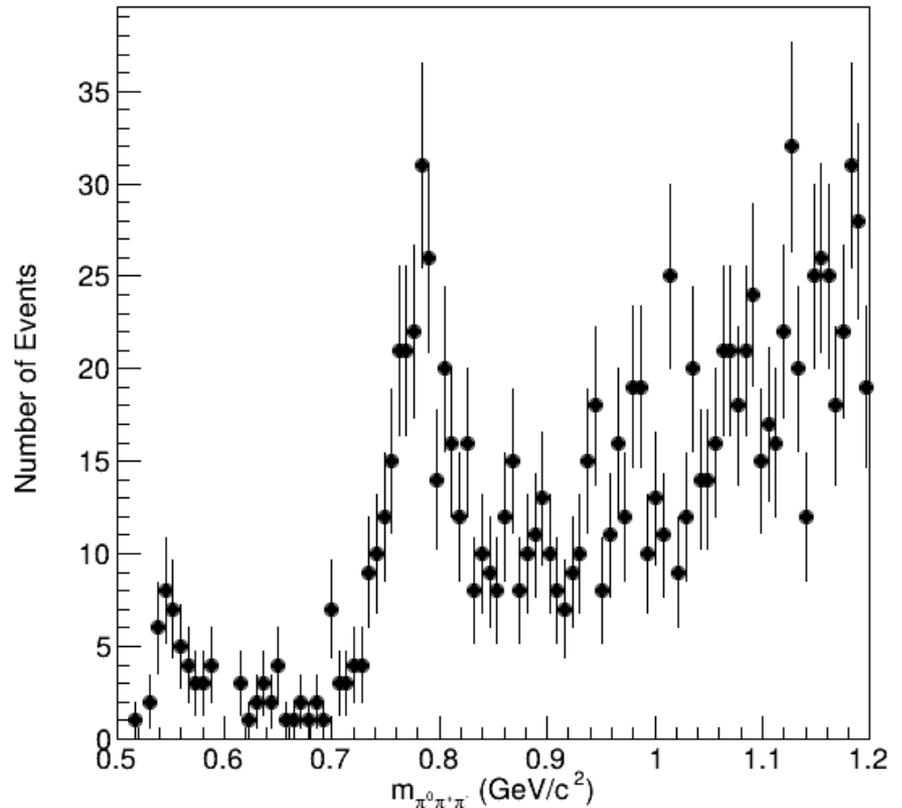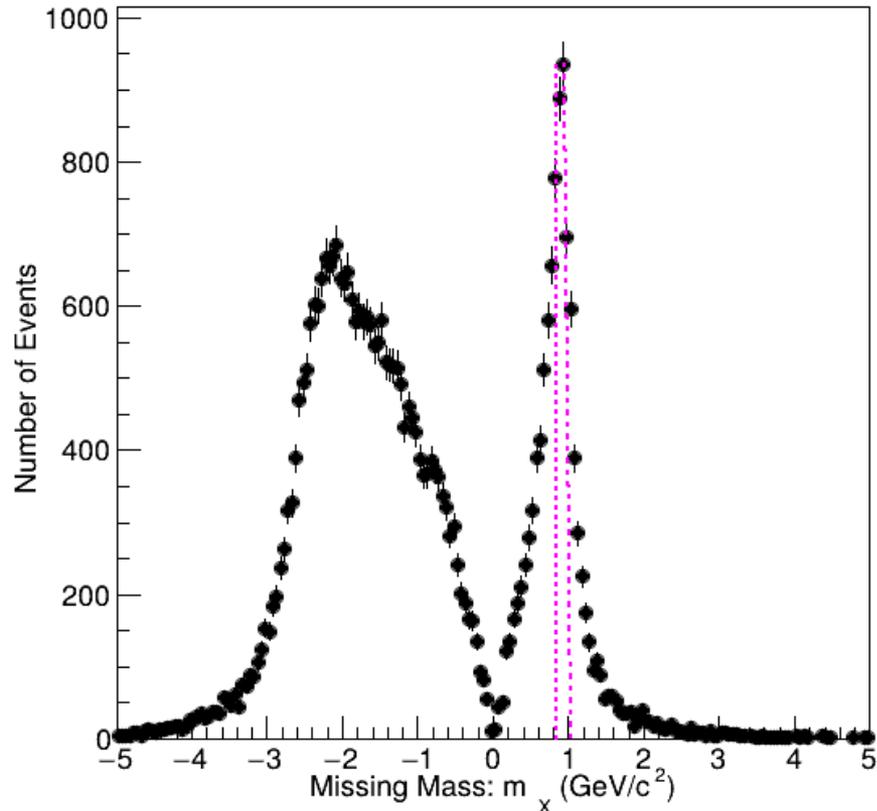
- Actually, if we have exactly 1 proton mass missing, we restore ω and η peaks
  - So the proton is actually missing?
  - The other two proton come from the other events?
- But these wrongly built events are relatively rare
- Note this mass not square, if the $m_X^2 < 0$, we keep the negative sign but take the square root on the absolute value of m_X^2

Proton Kinematics
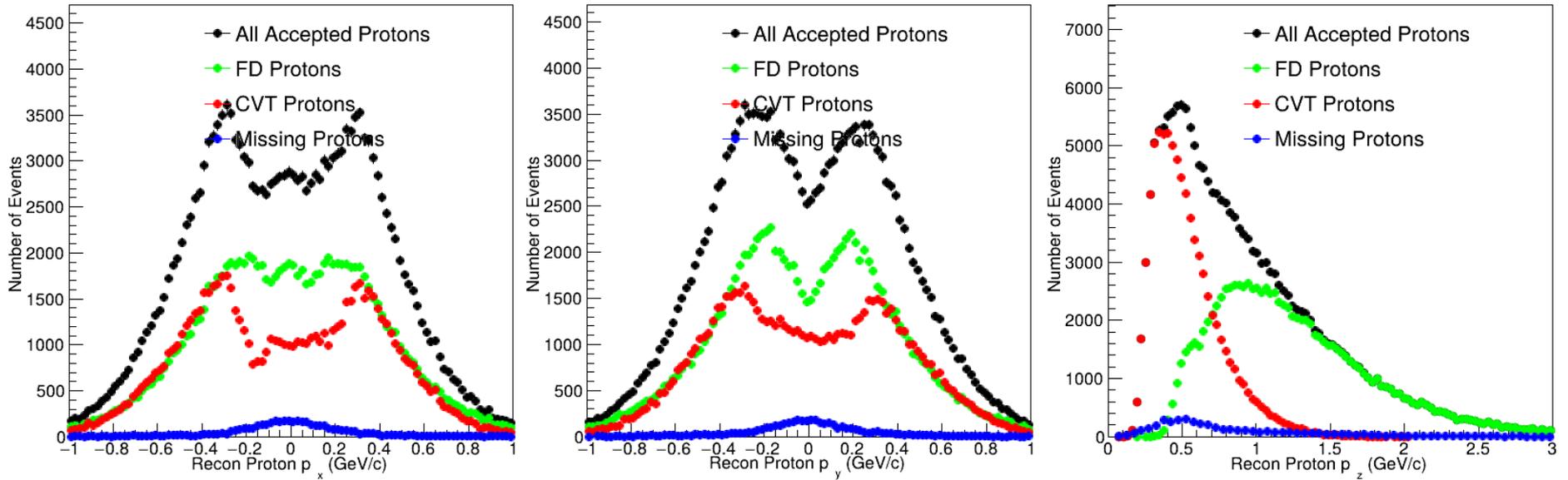
- Focusing on events where an ω meson is reconstructed, but the proton can be either also reconstructed or missing
- If reconstructed, we can see where the proton is accepted
- This may guild us how to run the MC simulations for acceptance studies

Data Structure of the Analysis Root File

- Root Tree file in Ntuple format
  - Two channels ($\gamma\gamma$ and $\pi^+\pi^-\gamma$) on separate root files

- Save event level Q^2, t

- Save the reconstructed π^0, ω, N^* hadron kinematics including invariant mass

- Keep the final states daughter particles: γ, p, e, and $\pi^\pm$

- Keep detector information (whole detector id) so you can get FD and CVT

- 4 Skimmed Data Samples
  - Torus-1 $\omega \rightarrow \pi^+\pi^-\pi^0$
  - Torus-1 $\omega \rightarrow \pi^0\gamma$
  - Torus+1 $\omega \rightarrow \pi^+\pi^-\pi^0$
 - Torus+1 $\omega \rightarrow \pi^0\gamma$

Event Level

```
Attaching file PiPi.root as _file0...
(TFile *) 0x7faa62d7bdc0
root [1] .ls
TFile**         PiPi.root
 TFile*         PiPi.root
  KEY: TTree    GammaPairTree;1 GammaPairTree
root [2] GammaPairTree->Show(1)
======> EVENT:1
 EvtID               = 414
 PairID              = 0
 QSquareVec          = (vector<float>*)0x600001389960
 tVec                = (vector<float>*)0x6000013899e0
 WVec                = (vector<float>*)0x600001389a60
 NPiP                = 1
 NPiM                = 1
 NP                  = 0
 NN                  = 0
 NKP                 = 0
 NKM                 = 0
 NElec               = 1
 NGamma              = 2
 NOther              = 0
```

Particle Level

```
 PDetVec             = (vector<int>*)0x600001370600
 ProtonPxVec         = (vector<float>*)0x600001370680
 ProtonPyVec         = (vector<float>*)0x600001370700
 ProtonPzVec         = (vector<float>*)0x600001370780
 PiPChi2Pid          = (vector<float>*)0x600001370800
 PiMChi2Pid          = (vector<float>*)0x600001370880
 PChi2Pid            = (vector<float>*)0x600001370900
 TripletMass         = 0.966974
 TripletPx           = 0.0626081
 TripletPy           = 0.795718
 TripletPz           = 5.54219
 TripletE            = 5.68225
 MissingMass         = 2.65577
 MissingPx           = -0.0520847
 MissingPy           = -0.741455
 MissingPz           = 4.40678
 MissingE            = 5.19859
 MissingMassPiZero   = 2.66318
 MissingPxPiZero     = -0.0520847
 MissingPyPiZero     = -0.741455
 MissingPzPiZero     = 4.40678
 MissingEPiZero      = 5.20238
 MissingMassOmega    = 4.55691
 MissingPxOmega      = 0
 MissingPyOmega      = 0
 MissingPzOmega      = 10.6
 MissingEOmega       = 11.538
```

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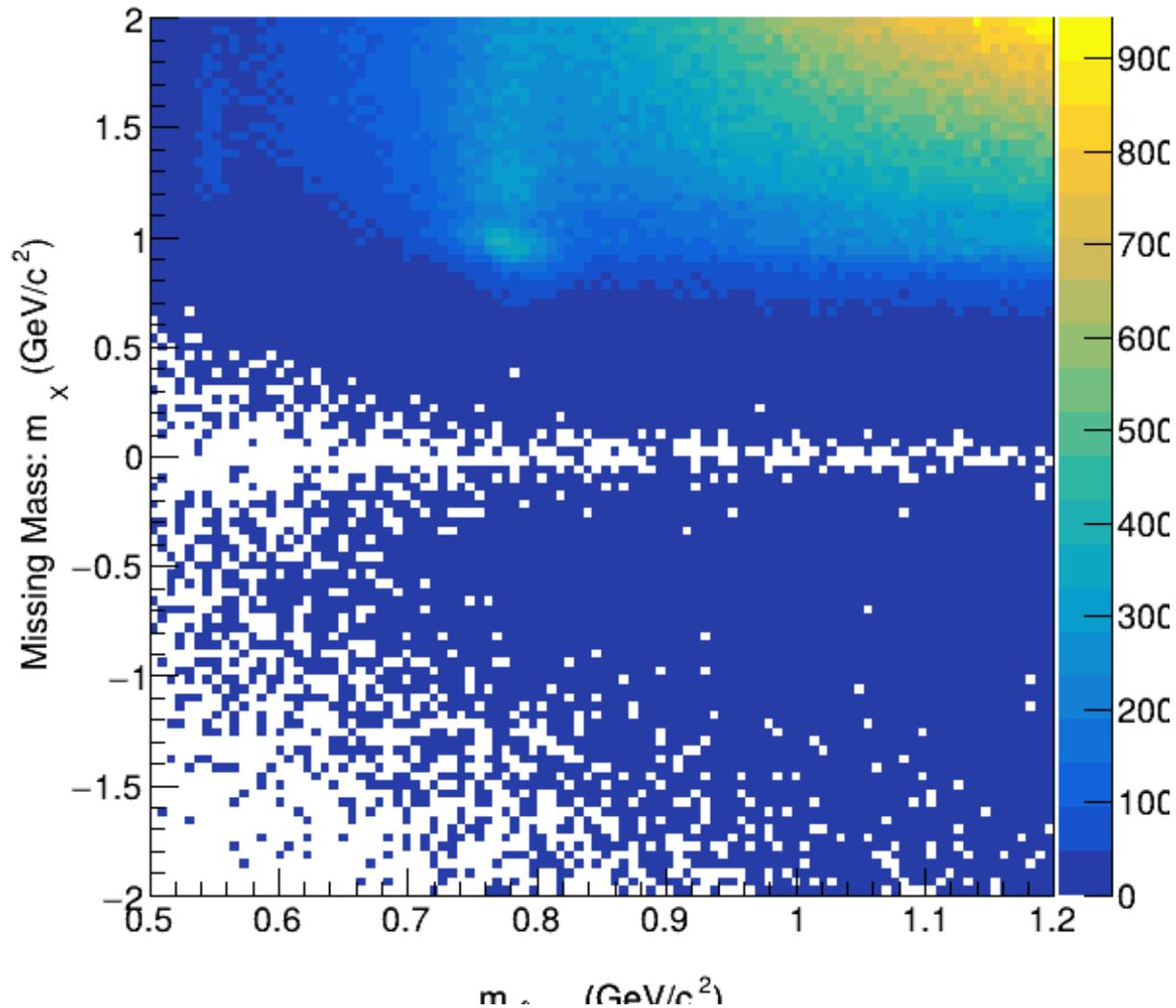
2D Correlations

- Clear Correlation between Missing Mass and the ω Mass